UPSTREAM CHANNEL CHANGES FOLLOWING DAM CONSTRUCTION AND REMOVAL USING A GIS/REMOTE SENSING APPROACH[1]

James E. Evans, Jennifer M. Huxley, and Robert K. Vincent[2]

ABSTRACT: This study used an innovative GIS/remote sensing approach to study historical river channel changes in the Huron River, a wandering gravel-bedded river in northern Ohio. Eight sets of historical aerial photographs (1958-2003) span the construction of a low-head dam (1969), removal of the spillway (1994), and removal of the dam itself (2002). Construction of the dam modified stream gradients >4 km upstream of the small impounded reservoir. This study tracked changes in the polygon size, shape, and centroid position of 12 sand-gravel bars through a study reach 0.2-4.1 km upstream of the dam. These bars were highly responsive, tending to migrate obliquely downstream and toward the outer bank at rates up to 9 m/year. Historical changes in the size and position of the bars can be interpreted as the downstream translation of one or more sediment waves. Prior to dam construction, a sediment wave moved downstream through the study reach. Following construction of the dam, this sediment wave became stationary and degraded *in situ* by dispersion. The growth of bars throughout the study reach during this time interval resulted in a progressive increase in channel sinuosity. Removal of the spillway rejuvenated downstream translation of a sediment wave through the study reach and was followed by a reduction in channel sinuosity. These results illustrate that important geomorphologic changes can occur upstream of low-head dams. This may be a neglected area of research about the effects of dams and dam removals.

(KEY TERMS: effects of dams; dam removals; fluvial geomorphology; sediment waves; GIS/remote sensing.)

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INTRODUCTION

Dams have had an enormous impact on the hydrology, sediment loads, and geomorphology of rivers. In the United States, the approximately 75,000 larger dams (NID, 2003) and approximately 2 million low-head structures (Graf, 1993) collectively store the equivalent of 1 year of runoff over the conterminous lower 48 states (Graf, 1999), an extraordinary manipulation of the hydrologic cycle. The sediment load of the Mississippi River to the Gulf of Mexico is approximately half that of pre-1950 due to dam construction on the Missouri and Arkansas Rivers (Meade, 1995). Reservoirs now drown approximately 600,000 linear miles of channels and floodplains in the United States (Heinz Center, 2002). At the present time, there are only 42 rivers in the United States that

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[2]Respectively (Evans, Vincent), Professor of Geology, Department of Geology, Bowling Green State University, 190 Overman Hall, Bowling Green, Ohio 43403; and Ph.D. Candidate, Department of Geography, Kent State University, Kent, Ohio 44242 (E-mail/Evans: evansje@bgsu.edu).

have free-flowing reaches greater than at least 200 km (Benke, 1990).

Studies on the impacts of individual dams have generally focused on the reservoir and on the channel reaches immediately downstream of the dam. Changes within the reservoir can include increased water depth, changes in temperature, possible development of density stratification, loss of light penetration due to turbidity, retention of nitrate and phosphate, growth of plankton and algae, and changes in aquatic ecosystems from lentic to lotic species (Baxter, 1977; Petts, 1984; Poff and Hart, 2002). In addition, it has been long documented that sediment accumulation in the reservoir will result in typical storage capacity loss rates of 0.5-1% per year (Dendy, 1968).

Downstream of the dam the most immediate impact is the degradation as the river reestablishes its sediment load by eroding bed and bank materials. Erosion downstream of a dam can cause incision and channel widening, preferential transport of fine-grained material, and resulting channel armoring which can have an adverse impact on benthic ecosystems (Petts, 1984). However, the most pervasive long-term effect is aggradation downstream due to flow regulation because the dam serves to attenuate the flood peaks that govern sediment transport in an unregulated river. The resulting deposition downstream affects channel morphology, substrate, and flood regime (Collier *et al.*, 1996; Chin *et al.*, 2002). Other downstream impacts can include changing the thermal structure of the river due to release of water from below the thermocline of the reservoir (Muth *et al.*, 2000), the effects of the dam as a barrier to anadromous fish migration (Baxter, 1977), and the effects of altered flood regime on riparian plant communities that depend on periodic inundation (Bayley, 1995; Wooten *et al.*, 1996; Nislow *et al.*, 2002).

The emerging science of dam removals has been reviewed elsewhere (Evans *et al.*, 2000a; Hart *et al.*, 2002; Heinz Center, 2002; Evans, 2003). Dam removals involve transient, dis-equilibrium effects that introduce new concerns for watershed management or restoration. The major new concerns include the fate of reservoir sediments (Evans *et al.*, 2000b, 2002; Doyle *et al.*, 2002, 2003; Pizzuto, 2002; Stanley and Doyle, 2002), the impacts of contaminated sediments (Shuman, 1995), and changes in downstream flood hazards (Roberts *et al.*, 2006).

In contrast to the above, there have been relatively few studies about the effects of dams or dam removals on the fluvial system upstream of the reservoir. The available literature tends to focus on three upstream issues: changes in flood regime (e.g., Leopold and Maddock, 1954), changes in riparian ecosystems (e.g., Shafroth *et al.*, 2002), and changes in sediment budgets (e.g., Faulkner and McIntyre, 1996; Evans *et al.*, 2000c). While some studies have looked at larger-scale historical channel changes in rivers that include dams (e.g., Gregory *et al.*, 2002), there is an absence of information about the response of individual features and overall geomorphic changes.

This paper applies a geographical information system (GIS)/remote sensing approach to the study of individual bars and channel pattern upstream of a low-head dam. It is our contention that even relatively small dams can be responsible for significant fluvial modifications upstream of the reservoir. Such upstream modifications are seldom considered in decision-making regarding dam construction or dam removal, yet may have important implications for the fluvial system and the emerging interest in river restoration.

METHODS

Huron River and Coho Dam

The Huron River is located in north-central Ohio (Figure 1). The river occupies a small drainage basin (1,052 km^2) and has a main channel length of 96 km. The Coho Dam is located at river kilometer (RK) 24.6, and the study area extends an additional 4.1 km upstream. There is a drainage area of 735 km^2 above the dam. The closest hydrologic structure located upstream of the study area is a low-head dam approximately 12.5 km upstream. There is a U.S. Geological Survey (USGS) gaging station at RK 20.6 with continuous gaging records from 1950-present except during the early 1980s. During this time interval, the Huron River had a mean annual discharge of 8.7 m^3/s, with a peak discharge of 1,405 m^3/s recorded in 1969 (USGS, 2005).

The Huron River flows basically south to north, down the Allegheny Escarpment and across the Lake Erie Coastal Plain into Lake Erie. Across the physiographic boundary is a two-order of magnitude change in stream gradient, from average gradients of 2.0×10^{-3} within the Allegheny Escarpment to average gradients of 3.3×10^{-5} within the Lake Erie Coastal Plain (Figure 2). The Coho Dam was constructed on the Allegheny Escarpment, near its base. Within the Allegheny Escarpment, the Huron River consists of alternating reaches of: (1) bedrock-incised channel consisting of riffles and small gravel bars (Figure 3a) and (2) sedimentation zones consisting of sinuous single or multiple channels with numerous larger sandy gravel bars (Figure 3b). The study area

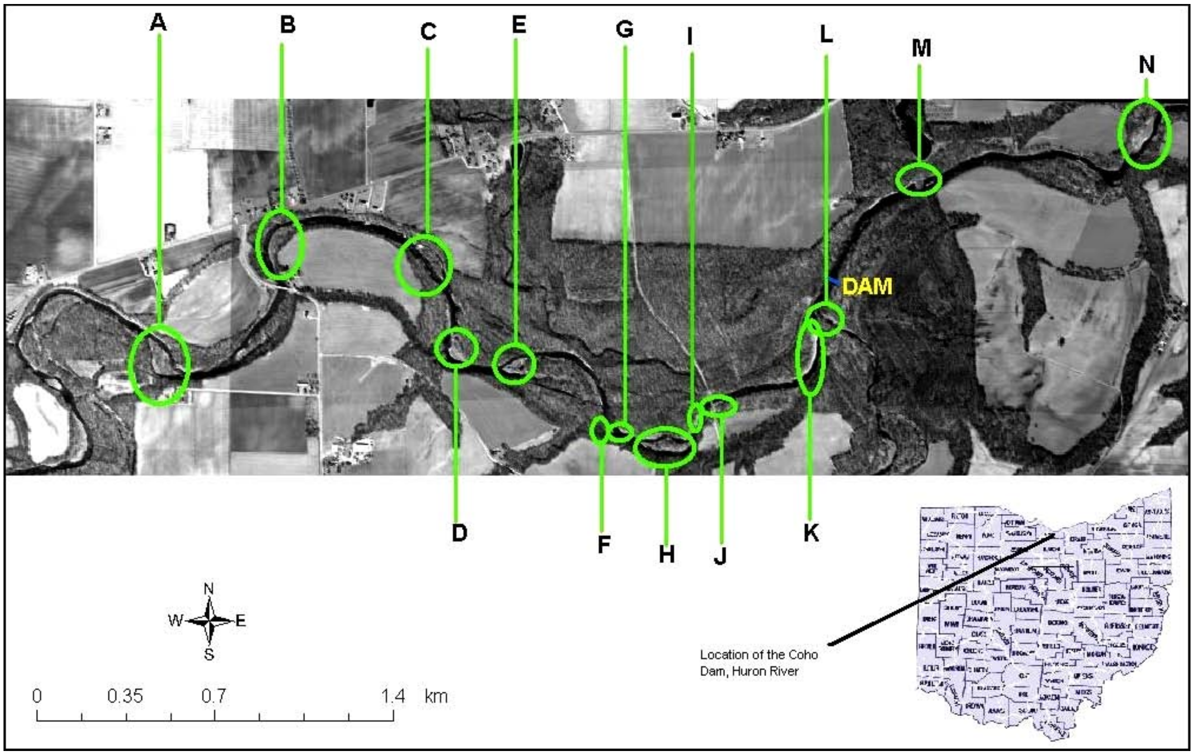

FIGURE 1. Aerial Photograph From 2001 Showing the Study Area (bedforms A-L), Upstream of the Coho Dam (right center), Huron River. The Huron River flows from left (west) to right (east). The insert map shows the location of the study area in north-central Ohio.

is one of these sedimentation zones and fits the criteria for a "wandering gravel channel" of Neill (1973) and Church (1983).

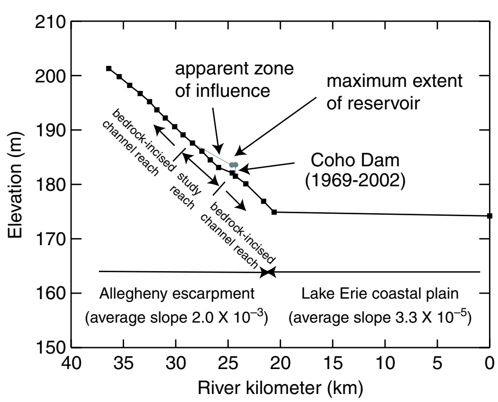

FIGURE 2. Longitudinal Profile for the Huron River, Showing the Position of the Coho Dam at the Base of the Allegheny Escarpment. The black line is pre- and post-dam, while the gray line shows the modifications in the longitudinal profile caused by the dam (1969-2002). The maximum extent of the reservoir was approximately 100 m, shown as the short horizontal line segment. The inclined gray line connects the upstream end of the reservoir (RK 24.7) to the upstream bedrock-incised channel (RK 28.7), which would be expected to respond slowly to changes in gradient. The gray line shows that aggradation would be expected in the 4.1 km study reach due to construction of the dam. See Discussion and Conclusions section for additional information.

The Coho Dam was a low-head structure 1.5 m high and 37 m wide that was constructed in 1969 by the Ohio Department of Natural Resources for fisheries enhancements. The dam was constructed at the upstream end of a bedrock-incised channel reach, drowning a set of rapids. The dam created a small reservoir, which at spillway-full elevation extended upstream approximately 100 m. The upstream study reach consists of noncohesive sand and gravel over approximately 4 km, until the start of another bedrock-incised reach. The dam was significantly modified by the removal of the weir board spillway in 1994 and the dam was entirely removed in 2002. Because the upstream sediments are noncohesive, removal of the dam did not result in visible nick point migration across the former reservoir surface.

The database of eight sets of historical aerial photographs (1958-2003) spans the life history of the dam from its construction in 1969 to final removal in 2002. A wider examination of the drainage basin over this time interval does not reveal any significant hydrologic changes such as channel diversions, modifications of upstream hydrologic structures, or introduction of new major sediment sources that could account for the changes discussed in this paper.

FIGURE 3. Photographs of the Huron River Showing (a) Bedrock-Incised Channel Reach (bedrock-floored and partly bedrock-sided channel) Immediately Upstream and Downstream of the Study Area and (b) Sedimentation Zone Consisting of Sand and Gravel Bars, Found in the Study Area Upstream of the Coho Dam.

Data Sources and Properties

The eight sets of historical aerial photograph are described in Table 1. The five aerial photograph sets from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) were paper layouts that were scanned at 1,000 dpi. The 1995 image from the Ohio Department of Administrative Services (ODAS, 2004) had been previously scanned at 1,000 dpi, corrected for parallax, and projected as a digital orthoquadrangle map (DOQ) using universal transverse mercator (UTM) coordinates (grid square R17) with the NAD 1983 CONUS datum. The 2001 and 2003 images from the Erie Country Auditor's Office were mosaics of aerial photographs for the entire county that had previously been scanned at 800 dpi. All of these digital images were manipulated using Earth Resources Data Analysis System Imagine® 8.5 for remote sensing and imported into Environmental Systems Research Institute (ESRI)® ArcGIS™ 8.3.

Image Processing

In order to compare historical aerial photographs, each image had to be georeferenced and projected

TABLE 1. Summary Data About Aerial Photographs and Stage Height Correction.

	Information About the Imagery				Stage Height Correction	
Agency Source	**Date Flown**	**Format**	**Image Scale**	**Pixel Dimensions**	**Mean Daily Stage Height(m)**	**Correction (%)**
USDA-NRCS	9/2/1958	Paper	1:6566	16.8 × 16.8 cm	1.68	−15
USDA-NRCS	5/25/1964	Paper	1:6566	16.8 × 16.8 cm	2.29	+14
USDA-NRCS	5/14/1971	Paper	1:6566	16.8 × 16.8 cm	1.89	−5
USDA-NRCS	4/2/1983	Paper	1:10526	26.7 × 26.7 cm	1.95	−2
USDA-NRCS	4/9/1988	Paper	1:10526	26.7 × 26.7 cm	1.83	−8
ODAS	3/15/1995	DOQ	1:12000	38.1 × 38.1 cm	1.98	0
Erie Co. Auditor	4/1/2001	Digital	1:12000	38.1 × 38.1 cm	1.89	−5
Erie Co. Auditor	4/12/2003	Digital	1:12000	38.1 × 38.1 cm	2.26	+13

Notes: (1) Mean daily stage height obtained from mean daily discharge on that date and rating curve from USGS gaging station located approximately 4 km downstream of the dam. (2) The areas of the bedform polygons were adjusted by this correction factor to account for differences in stage height. The 1995 image was arbitrarily selected as the reference stage height (0% correction). See text for discussion.

NRCS = Natural Resources Conservation Service, ODAS = Ohio Department of Administrative Services, USGS = U.S. Geological Survey, DOQ = digital orthoquadrangle map.

into the UTM coordinate system. Because the 1995 image had been georectified and projected into a DOQ, the seven other historical aerial photographs were rubber-sheeted to the 1995 image. Rubber-sheeting is justifiable in a study area which has <25 m topographic relief. Three manually selected tie-points were matched between each image and the DOQ. Additional tie-points were subsequently obtained by triangulation using a polynomial fit that minimizes root mean square (RMS) error. The five images produced from the NRCS as paper layouts had relative RMS errors less than 0.05 pixels, compared with other pixels in the same image. The two digital images produced from the Erie County Auditor's office had relative RMS error less than 1 pixel. The differences in RMS errors between the two datasets is related to the original scale and scanning resolution (Table 1). Rubber-sheeting involved randomly selecting 20 tie-points between each image and the DOQ, then stretching each image to match the DOQ. The georectified images were then imported into ArcGIS. A final error analysis involved finding the UTM coordinates of five random selected points from each image and from the DOQ and finding the RMS error as a linear distance assuming that the DOQ was perfectly georectified. The RMS errors between each image and the 1995 DOQ ranged from 2.51 to 5.02 m (average RMS error of 3.28 ± 0.84 m). This error is primarily caused by the fact parallax in the aerial photographs is only partly corrected by rubber-sheeting the images to the DOQ.

Analysis of Bedforms

Twelve sand-gravel bars were selected for this project based upon morphology, size, location, and visibility throughout the study interval (1958-2003) regardless of stage height (Table 2). Huxley (2004)

TABLE 2. Characteristics of Bedforms in the Study Area in 2003.

Label	Feature*	Length (m)	Width (m)	L/W Ratio	Area (ha)	Perimeter (m)
A	Medial Bar	134.4	65.2	2.1	0.709	436.5
B	Lateral Bar	128.1	109.4	1.2	0.454	378.9
C	Lateral Bar	137.3	98.2	1.4	0.364	378.7
D	Lateral Bar	113.6	60.5	1.9	0.215	285.7
E	Medial Bar	74.9	54.2	1.4	0.191	206.9
F	Confluent Bar	63.1	34.8	1.8	0.089	156.8
G	Lateral Bar	46.9	37.8	1.2	0.059	134.1
H	Medial Bar	191.7	58.6	3.3	0.639	449.5
I	Confluent Bar	33.2	34.1	1.0	0.035	103.0
J	Lateral Bar	57.9	69.6	0.8	0.113	189.5
K	Lateral Bar	204.0	96.7	2.1	0.255	226.1
L	Confluent Bar	86.4	57.4	1.5	0.368	314.1

*Bar terminology from Miall (1977) and Bristow *et al.* (1993).

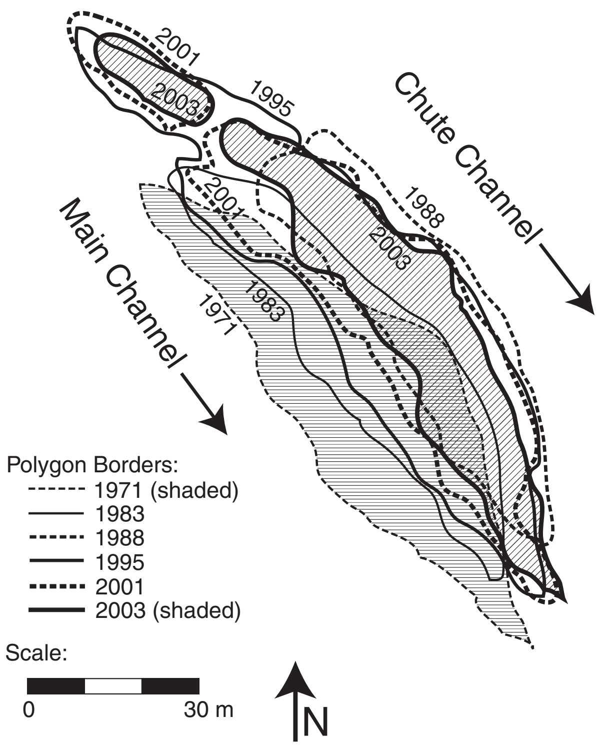

FIGURE 4. Changes in the Size, Shape, and Position of Bedform C From 1971-2003. For ease of viewing, the polygons for 1958 and 1964 are not shown and the 1971 and 2003 polygons are shaded. This shows that despite shifts in size and position, the bedform retained its approximate shape.

also looked at two additional bars downstream of the dam, but the results were inconclusive because each was severely eroded following closure of the dam. As mentioned earlier, the study area is delimited by significant channel changes as the river becomes a bedrock-incised channel both upstream and downstream of the study reach.

For each historical image, a shapefile was created for each of the 12 bedforms using ArcGIS. Polygons were drawn around each bedform at the waterline for the day the image was collected (Figure 4). The shapefiles were imported into a geodatabase and converted to a feature class, which populate the attribute table of the properties of the polygon. With the use of a macro, the UTM position of the polygon was calculated and the UTM coordinate system was added to their attribute table in order to create bedform centroids and track their change in position using UTM coordinates.

Ground Truthing

A number of features visible on the April 2003 image were used for ground-truthing during October 2003. Ground Control Points (GCPs) were established at recognizable features such as road junctions and the abutments of a bridge. In addition, the UTM position of distinctive features on several bars was recorded. Field measurements were made using differential global positioning satellite (GPS) with a base station and rover receiver, with a UTM coordinate accuracy of 0.50 ± 0.11 m for this study. The positions of the GCPs were compared with the rubber-sheeted 2003 image and found to have RMS errors that ranged from 1.36 to 2.91 m (average RMS error of 1.95 ± 0.63 m). These are consistent with the RMS error of 2.51 m determined earlier between the rubber-sheeted 2003 image and the georectified 1995 DOQ.

Corrections for Stage Height Differences

The eight historical aerial photographs were collected on different days and different years. This implies that differences in stage height would become a variable affecting the exposed surface area of each bar on each photo. To correct this, we obtained the mean daily discharge for the days the photos were collected and used the rating curve from the USGS gaging sta-

TABLE 3. Change in Bedtorm Area Over Time.

	Bedform Size (adjusted areas in ha)											
Year	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
1958	0.556	0.170	0.204	0	0.114	0.036	0.041	0.536	0.513	0.093	0.338	0.117
1964	0.639	0.276	0.377	0.079	0.194	0.048	0.036	0.597	0.011	0.156	0.317	0.272
1971	0.650	0.421	0.452	0.283	0.100	0.106	0.117	0.578	0.046	0.077	0.306	0.203
1983	0.664	0.442	0.347	0.227	0.235	0.118	0.083	0.684	n/a	0.029	0.336	0.350
1988	0.665	0.610	0.325	0.219	0.181	0.117	0.048	0.601	n/a	0.019	0.129	0.259
1995	0.751	0.589	0.400	0.220	0.182	0.071	0.062	0.598	n/a	0.115	0.243	0.319
2001	0.766	0.542	0.493	0.293	0.272	0.142	0.077	0.660	n/a	0.177	0.366	0.219
2003	0.948	0.550	0.403	0.169	0.248	0.126	0.021	0.831	n/a	0.258	0.368	0.305

Note: Bedform areas were adjusted to a reference stage height to allow comparisons.

TABLE 4. Rate of Change of Bedform Area.

Interval	Rate of Change of Bedform Area (%/year)											
	A	B	C	D	E	F	G	H	I	J	K	L
1958-64	2.5	10.4	14.1	17.0	11.7	5.1	−2.2	1.9	−16.3	11.4	−1.0	22.0
1964-71	0.2	7.5	2.9	36.4	−6.9	17.4	32.6	−0.5	44.2	−7.3	−0.5	−3.6
1971-83	0.2	0.4	−1.9	−1.7	11.2	1.0	−3.5	1.5	n/a	−5.2	0.8	6.1
1983-88	0.0	7.6	−1.3	−0.7	−4.6	0.0	−3.5	−2.4	n/a	−7.1	−12.3	−5.2
1988-95	1.8	−0.5	3.3	0.0	0.1	−3.3	4.6	−0.1	n/a	73.0	12.5	3.4
1995-2001	0.3	−1.3	3.9	2.6	8.2	16.6	4.6	1.7	n/a	9.1	8.5	−5.2
2001-03	11.8	0.7	−9.2	−21.0	−4.5	−5.7	−36.2	12.9	n/a	22.8	0.2	19.7

tion located 4 km downstream of the dam to obtain the mean daily stage height for those days (Table 1). Because almost all of the aerial photographs were collected at the same time of year, the total variability in stage height for all of the aerial photographs was only 0.41 m. A “reference stage height” was arbitrarily selected from the middle of the range, and the surface area of each bar was proportionally adjusted to that reference stage height (Table 3). The correction changed the exposed surface area of most of the bedforms by less than ±8%, with maximum changes of ±15%. The changes in surface area over time were then converted to annual rates (Table 4).

Correcting for stage height differences could also affect the shape of the bedform and hence the position of the bedform centroid. Because the data came from two-dimensional images, it was not possible to make a shape correction. Therefore, bedform stability was assessed semi-quantitatively by looking at changes in the length (L) to width (W) ratio of selected bars over time. Certain bars were excluded if their change in shape was attributable to other factors such as bar amalgamation or accretion to the channel margin. In the example shown (Figure 4), the L/W ratio remained reasonably consistent between 1958 and 1988 (the L/W ratio fluctuated less than 24%). Between 1988 and 1995, the bedform elongated and narrowed, and then the L/W ratio again remained reasonably consistent from 1995-2003 (the L/W ratio fluctuated less than 18%). Throughout this interval, the bar changed significantly in size and position. As this example illustrates, changes in stage height alone did not significantly alter the shape of the bars.

Translation Rates and Directions

For each bedform, the position of bar centroids was plotted on a UTM grid which was subsequently rotated to be thalweg-parallel (Figure 5). Changes in position could be calculated as linear distances upstream or downstream (Table 5) or laterally toward the inner bank or outer bank (Table 6). Finally, the thalweg-path distance from the bar centroid to the spillway of the dam was calculated over each time interval (Table 7).

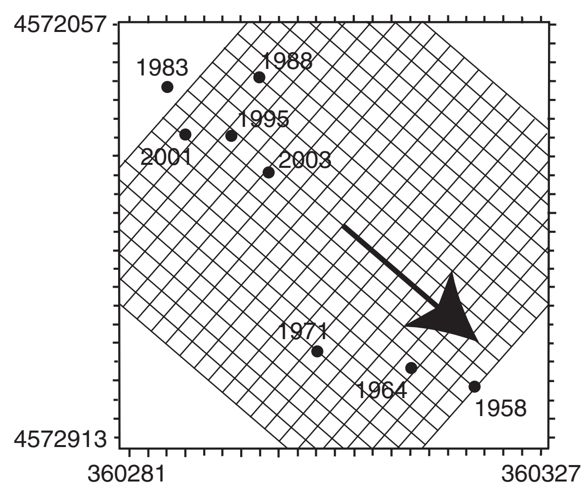

FIGURE 5. Example of Change in Location of the Bedform Centroid Over Time, From Bedform A. The edges show UTM coordinates, while the grid with 2 m spacing has been rotated to be thalweg-parallel. Arrow shows flow direction.

RESULTS

Trends in Bedform Responses

The bars exhibited a range of behaviors that are summarized in Table 8. For example, if the bar increased in size at the same time the bar centroid shifted downstream this was interpreted as bar-tail deposition, while if the bar decreased in size while the centroid shifted downstream this was interpreted as bar-head erosion. Similarly, if the bar increased in size, while the centroid shifted laterally toward the outer bank, this was interpreted as accretion on the outer margin of the bar, while if the bar decreased in

TABLE 5. Change in Centroid Position Upstream/Downstream.

Interval	Rate of Change of Centroid Position (m/year)											
	A	B	C	D	E	F	G	H	I	J	K	L
1958-64	–1.2	–1.9	–0.3	n/a	–2.0	–1.8	0.2	0.1	–0.8	–0.9	0.7	0.8
1964-71	–1.2	2.2	0.4	1.4	2.0	1.2	–2.6	0.2	0.3	2.8	–2.2	1.4
1971-83	–2.6	0.6	–0.8	–3.2	2.2	–0.5	0.3	0.8	n/a	0.7	0.5	–1.3
1983-88	1.3	0.9	0.1	–0.1	2.0	–0.1	0.3	2.6	n/a	3.0	5.2	1.3
1988-95	0.2	–2.7	–2.7	0.3	–1.0	0.8	1.1	–0.7	n/a	–4.5	0.3	1.4
1995-2001	–0.6	2.3	2.6	3.2	–0.5	–0.4	1.1	0.7	n/a	–0.3	2.6	–0.1
2001-03	4.7	–7.5	3.2	9.0	0.9	1.0	9.3	0.6	n/a	0.9	–9.1	1.5

Notes: Positive rates are downstream and negative rates are upstream.

TABLE 6. Change in Centroid Position Laterally.

Interval	Rate of Change of Centroid Position (m/year)											
	A	B	C	D	E	F	G	H	I	J	K	L
1958-64	0.5	0.3	–1.2	n/a	–1.6	–0.8	–0.2	0.2	–2.1	1.3	–1.0	–2.2
1964-71	0.7	–0.1	–0.5	0.9	–0.4	0.2	–2.2	–0.2	–0.1	–0.5	–2.1	0.6
1971-83	0.9	0.6	0.8	0.3	2.0	0.4	1.0	–0.4	n/a	0.2	0.3	0.3
1983-88	1.4	–2.3	3.7	–2.6	–0.9	0.4	1.0	–1.6	n/a	1.7	3.6	0.7
1988-95	–0.9	0.4	–2.4	0.4	–2.0	0.4	0.8	1.8	n/a	–2.4	1.7	1.5
1995-2001	–0.6	0.5	1.7	1.6	0.2	–0.1	0.8	0.9	n/a	–1.2	0.3	–0.8
2001-03	1.5	–0.6	1.6	1.6	0.9	1.0	0.5	–1.0	n/a	–1.4	–3.5	1.6

Notes: Positive rates are toward the outer bank and negative rates are toward the inner bank.

TABLE 7. Thalweg-Path Distance to Centroid From Fixed Point.

Year	Thalweg-Path Distance to Centroid (km)											
	A	B	C	D	E	F	G	H	I	J	K	L
1958	3.93	3.09	2.41	n/a	1.79	1.29	1.22	1.03	0.80	0.78	0.31	0.15
1964	3.93	3.08	2.41	2.07	1.80	1.27	1.22	1.03	0.80	0.77	0.31	0.15
1971	3.97	3.08	2.42	2.07	1.82	1.27	1.24	1.03	0.80	0.75	0.32	0.15
1983	4.01	3.09	2.44	2.11	1.81	1.26	1.24	1.03	n/a	0.75	0.33	0.17
1988	4.03	3.11	2.46	2.11	1.81	1.28	1.25	1.02	n/a	0.75	0.31	0.17
1995	4.07	3.16	2.48	2.11	1.85	1.31	1.26	1.05	n/a	0.78	0.30	0.17
2001	4.11	3.19	2.54	2.12	1.87	1.32	1.28	1.06	n/a	0.79	0.28	0.17
2003	4.08	3.18	2.52	2.09	1.85	1.30	1.24	1.05	n/a	0.79	0.30	0.16

Note: Distances are measured as thalweg-path length upstream from the spillway of the dam.

size while the centroid shifted toward the outer bank, this was interpreted as erosion (cutting of chute channels) on the inner margin of the bar. In general, these bars showed a tendency toward oblique migration downstream and toward the outer bank (Table 8c).

Trends in Change of Bedform Size

The results suggest that the bars change size and position over time. Figure 6 is a series of histograms showing the percentage increase (positive values) or decrease (negative values) in the size of each bar over specific time intervals. Note that Figure 6 can be misleading because it shows the annual rate-of-change in the size of each bar rather than the absolute size. For example, bar A grew continuously from 1958-2003, while bar K fluctuated in size, but ended in 2003 at approximately the same size as it began in 1958 (Table 3).

Figure 6 is interpreted to show that regions in the stream functioned as sedimentation zones (positive rates of increase of bedform size), transport zones (rate of change of bedform size approaches zero), or erosion zones (negative rates of increase of bedform size) over specific time intervals. Shifts in the position of sedimentation and erosion zones over time can be interpreted as the downstream translation of one

TABLE 8. Bedform Spatial and Temporal Responses.

A

		Upstream/Downstream Change in Centroid Position Over Time	
		Shifts Upstream (–)	**Shifts Downstream (+)**
Change in Bedform Volume Over Time	Decrease (–)	Bar-tail Erosion 10.6%	Bar-head Erosion 29.3%
	Increase (+)	Bar-head Deposition 28.0%	Bar-tail Deposition 32.0%

Note: n = 75.

B

		Lateral Change in Centroid Position Over Time	
		Towards Inner Bank (–)	**Towards Outer Bank (+)**
Change in Bedform Volume Over Time	Decrease (–)	Lateral (Outer) Erosion 14.7%	Lateral (Inner) Erosion 26.7%
	Increase (+)	Lateral (Inner) Deposition 26.7%	Lateral (Outer) Deposition 32.0%

Note: n = 75.

C

		Lateral Change in Centroid Position Over Time	
		Towards Inner Bank (–)	**Towards Outer Bank (+)**
Change in Centroid Position Over Time	Shifts Upstream (–)	Oblique Migration Upstream/Inner Bank 21.3%	Oblique Migration Upstream/Outer Bank 17.3%
	Shifts Downstream(+)	Oblique Migration Downstream/Inner Bank 21.3%	Oblique Migration Downstream/Outer Bank 40.0%

Note: n = 75.

or more sediment waves (see Discussion and Conclusions).

Trends in Bedform Centroid Location

There were two methods used to assess changes in the position of the bar centroid over time. First, the UTM coordinate of the centroid of each bar can be tracked sequentially. Such changes could be summarized (Table 9) into pre-dam (1958-69), interval of the dam (1969-2001) and post-dam (2001-03) behavior. These data show significant changes for each bedform, but do not present a clear picture of systematic changes in the fluvial system.

The second method involved is calculating the thalweg-path distance between the centroid of each bar and a fixed point, in this case the center spillway of the dam. Figure 7 demonstrates that most of the bars showed the following three-part trend: (1) prior to dam construction, the bar centroids remained approximately the same thalweg-path distance from the fixed point; (2) after construction of the dam, the centroids shifted upstream (increasing the thalweg-path distance from the fixed point); and (3) after dam removal, the centroids shifted back downstream (decreasing the thalweg-path distance from the fixed point). These changes can also be represented as changes in sinuosity (see Discussion and Conclusions). Sinuosity is an important geomorphic parameter of channel pattern and is defined as the ratio of thalweg-path distance to downvalley axis distance (Table 10).

DISCUSSION AND CONCLUSIONS

Backwater Effects

In this paper, the term "backwater effects" is used to refer hydrologic changes in the upstream reach that are related to the construction or removal of a downstream hydraulic structure, in this case a dam. The extent of the upstream reach influenced by backwater effects is called the "apparent zone of influence" (Figure 2). The word "apparent" is used because this study is a historical reconstruction of hydrologic events and was not accompanied by field channel surveys in 1969, for example. We believe the

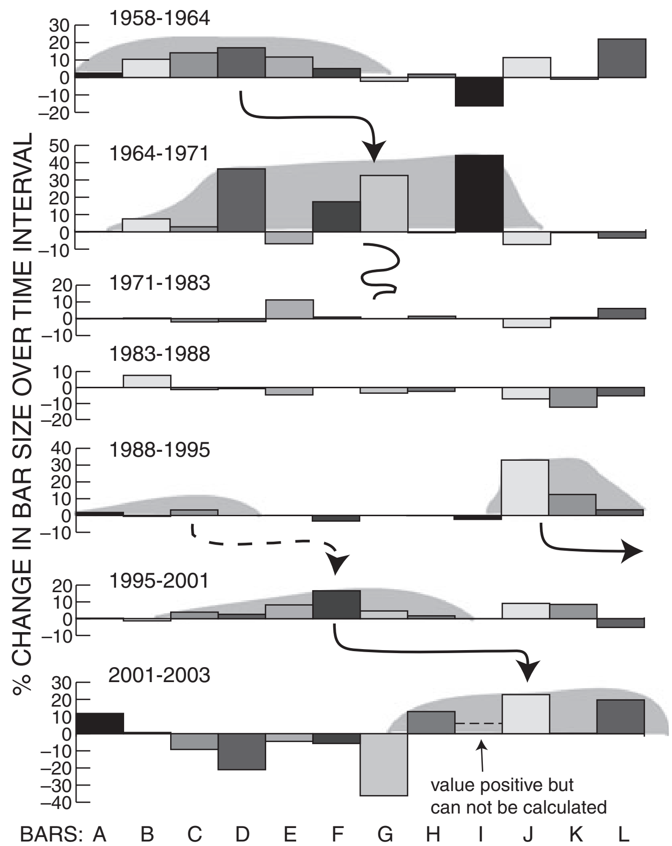

FIGURE 6. Time Interval Slice Showing the Annual Rate of Change of Bedform Size (percentage change in area/year). Shaded areas and arrows emphasize change in position of a depositional zone over time. The data is interpreted to show downstream migration of a sediment wave (A-F in 1958-64 and D-I in 1964-71) that ceases translation (1971-83) then decays *in situ* by dispersion (1983-88 and 1988-95) following dam closure in 1969. Removal of the dam (weirboard spillway in 1994 and dam in 2002) rejuvenated movement of sediment waves through the study reach (A-C in 1988-95, C-K in 1995-2001, and H-L in 2001-03). See text for discussion.

documented changes in channel and bedform geometry are due to the construction and removal of the dam. An examination of the historical aerial photograph database and other historical records do not indicate modifications of upstream structures, channel diversions, or variations in sediment supply that would provide alternative explanations.

It is widely acknowledged in the hydrologic literature that construction of a dam modifies hydraulics and sediment transport within the newly created reservoir. However, it is apparently contentious whether changes in hydraulics and sediment transport would occur further upstream of the reservoir. This illustrates a surprising disconnect between the hydrologic literature and studies of sequence stratigraphy related to late Cenozoic sea level change. For example, Holocene sea level rise to its present elevation of mean sea level (MSL) resulted in aggradation of the Colorado River (Texas). At a point 50 km inland of the modern coast, the Colorado River aggraded approximately 20 m to a present elevation of 30 m above MSL and aggradation extended further upstream to the long-profile crossover point (upstream limit of sea level influence) which is approximately 90 km inland, at an elevation 45 m above MSL (Blum and Tornqvist, 2000). Similar results have been observed for many rivers. Lane (1955) recognized that changes in base level result in vertical shifts in the equilibrium profile of rivers, manifested as either incision or aggradation, providing the conceptual basis for these observations. Current studies use more complicated conceptual models (e.g., Schumm, 1993; Blum and Price, 1998; Dalrymple *et al.*, 1998), mathematical models (e.g., Paola, 2000), and detailed flume studies (e.g., Heller *et al.*, 2001; Strong and Paola, 2006) to reproduce the stratal patterns observed in seismic lines of fluvial systems upstream of the delta and coastline, in response to base level changes and other long-term, large-scale geological processes not relevant to this discussion (such as paleoclimate change and tectonic subsidence).

Figure 2 shows the modifications in the longitudinal profile that were caused by the construction of the Coho Dam in 1969. The reservoir, extending

TABLE 9. Analysis of Resultant Vectors for Bedform Centroid Movement.

Bedform Label	Pre-Dam (1958-69)	Interval of Dam (1969-2002)	Post-Dam (2001-03)
A	Upstream	Upstream	Downstream
B	Lateral	Downstream	Upstream
C	Lateral	Lateral	Downstream
D	Downstream	Lateral	Lateral
E	Upstream	Downstream	Downstream
F	Lateral	Lateral	Lateral
G	Upstream	Lateral	Downstream
H	Stationary	Downstream	Lateral
1	Lateral	Lateral	Downstream
J	Downstream	Upstream	Upstream
K	Lateral	Downstream	Upstream
L	Lateral	Lateral	Lateral

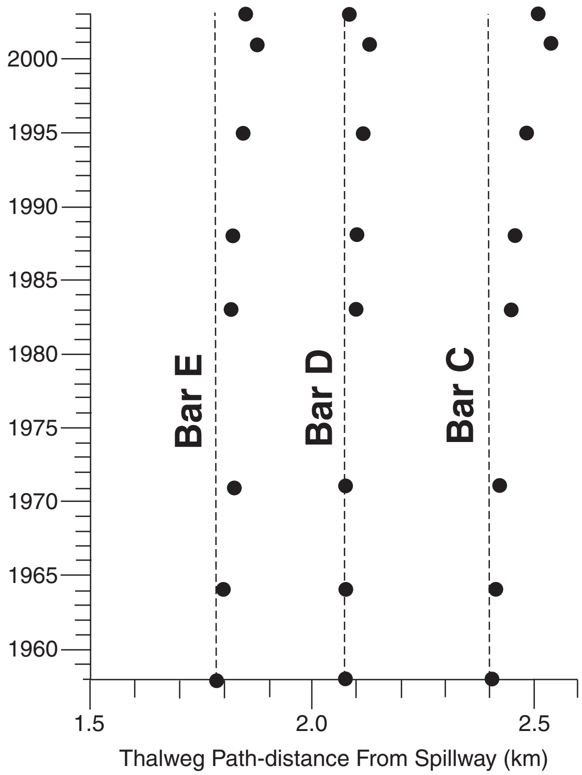

FIGURE 7. An Example of the Effect of the Coho Dam on the Sinuosity of the Huron River Upstream of the Dam. The figure shows the change in thalweg-path distance from the bedform centroid to the spillway of the dam for bars C, D, and E. Dashed lines reference the position of the bars with respect to 1958. In each case, there is little change in thalweg-path distance prior to the construction of the dam in 1969. Following closure of the dam in 1969, the three bedforms show increasing thalweg-path distances. This is interpreted as an increase in sinuosity due to bar growth during this time interval. Following the removal of the dam in 2002, the thalweg-path distance decreased. This is interpreted as a decrease in sinuosity due to the cutting of chute channels and erosion of bedforms. The patterns are similar for all of the bedforms in the study area. See text for additional discussion.

approximately 100 m upstream of the dam (RK 24.6-24.7), is shown as a short horizontal line segment. The longitudinal profile upstream of RK 28.7 is bedrock-incised channel and would be expected to adjust relatively slowly to changes in gradient (e.g., Schumm, 1993). Accordingly, the gray line segment in Figure 2 connects the downstream position of the bedrock-incised channel (RK 28.7) with the upstream position of the reservoir (RK 24.7). This line is for illustration purposes only. Because this is a historical reconstruction, it is probable that the actual profile through the study reach was a series of line segments. However, those separate line segments (if they existed) would have averaged to the line segment shown. The purpose of Figure 2 is to show that modification of the longitudinal profile, caused by construction of the dam, should have resulted in aggradation throughout the 4.1 km study reach, which is what the results demonstrate.

Sediment Waves

Sediment waves are transient zones of sediment accumulation that evolve by interactions between flow and sediment transport as they propagate through some particular channel reach (Sutherland *et al.*, 2002). Studies on both natural sediment waves and flume models indicate that the properties of individual sediment waves depend upon the relative rates of dispersion and translation (Nicholas *et al.*, 1995; Lisle *et al.*, 1997, 2001; Pizzuto, 2002). Field studies have focused on "slugs" of sediment introduced to a channel due to landslides and outburst floods due to the failures of natural and artificial dams (reviewed in Doyle *et al.*, 2002). Flume-based studies rely upon introducing a volume of sediment to an equilibrium channel. The results from both natural and flume studies suggest cases of pure translation or pure dispersion may be rare, however gravel-rich sediment slugs tend to attenuate *in situ* by dispersion (Lisle *et al.*, 2001).

Several caveats must be made at this point. First, flume-based studies use bed elevation and grain-size data to evaluate sediment wave behavior. In contrast, field-based studies typically have relied upon the recognition of bedforms, which raises issues of scale and bedform age (Lisle *et al.*, 2001). Second, different methods of analysis have been used in field-based

TABLE 10. Example of Change in Sinuosity for Bar A.

Date	Thalweg-Path Distance (m)	Valley-Axis Distance (m)	Sinuosity	Percentage (%) Change
1958	3929.3	2603.6	1.51	
1964	3930.1	2610.5	1.51	−0.2
1971	3972.5	2620.6	1.52	0.7
1983	4004.7	2636.4	1.52	0.2
1988	4029.9	2626.2	1.53	1.0
1995	4071.1	2629.1	1.55	0.9
2001	4113.1	2634.5	1.56	0.8
2003	4076.1	2625.3	1.55	−0.6

studies. This study differs significantly from those previous studies, which tracked a single sediment wave initiated from a point of disturbance (landslide toe, dam breach, etc.). In this case, there is no evidence for change in upstream rate of sediment supply. Throughout this study (1958-2003), the upstream basin remained approximately 90% agricultural (mostly row crops) that discharged sediment into the channel via a diffuse network of tile drains and drainage ditches. Finally, this study was based upon the behavior of larger bedforms (bars) which were recognizable on aerial photographs (i.e., exposed during low flow conditions). Thus we could not account for the behavior of smaller bedforms such as individual dunes that may have remained subaqueous at the times aerial photographs were collected.

Despite these caveats, we believe our results (Figure 6) show the following. During 1958-64, a sedimentation zone developed at the upstream portion of the study area (A-F) as indicated by bar growth rates of 5-10% per year. Downstream of F the bars alternate decay (negative rates) or growth (positive rates). By 1964-71, the locus of high rates of sediment accumulation had shifted downstream (D-I). We interpret the downstream movement of the locus of sedimentation from 1958-64 to 1964-71 as the downstream translation of a sediment wave.

After closure of the dam (1969), the sediment wave did not translate further downstream, and in subsequent years, it attenuated in place. The interval 1971-83 was a transitional phase where the sedimentation zone remained in one location (bars E-H continued to grow, but at reduced sediment accumulation rates). Between 1983 and 1988, most of the study area (bars C-L) was erosional. We interpret this change to indicate *in situ* dispersion of the sediment wave. The change from translation to dispersion can probably be attributed to two factors: reduced upstream sediment input due to loss of transport capacity (reduced water surface slope following dam closure) and a deficit in the downstream sediment budget implied by initial filling of the reservoir.

The fluvial system changed from erosional to mostly transportational between 1988 and 1995, with the exception of growth of bedforms immediately upstream of the small reservoir. Such transition may indicate adjustment of the sediment budget to changed hydrologic conditions. Following removal of the weir-board spillway in 1994, the Coho Dam ceased to be a hydrologic structure. A second sediment wave may have initiated in 1988-95 (bars A-C), but can more clearly be observed in the positive growth rates of bars C-K in 1995-2001 and in the positive growth rates of H-L in 2001-2003. (Note: Bar I could not be evaluated from 1995 to 2001 or 2001 to 03 because it grew downstream into the shadow of a bridge span; however, the growth rates were clearly positive in both cases.) We interpret the 1995-2001 and 2001-03 data to show renewed downstream translation of a sediment wave following effective removal of the dam.

Finally, it should be noted that the data cannot be explained by the incident of major floods. The largest floods of record (ranked from largest to smallest) occurred in 1969, 1959, 1998, 1992, and 1961. None of these larger floods occurred in the interval we interpret as *in situ* dispersion of the sediment wave (1971-88) following dam closure.

Changes in Sinuosity

The thalweg-path distance between two points can change over time depending upon depositional growth of bars or the erosional cutting of chutes in the intervening distance. Changes in thalweg-path distance indicate changes in sinuosity of the channel, which in this study changed by about 1% (Table 10). Following construction of the dam, the upstream-shift in bar centroids shown in Figure 7 can be interpreted to show increasing channel sinuosity due to deposition (bar-growth) in the channel. Following removal of the dam, the downstream-shift in bedform centroids shown in Figure 7 can be interpreted to show decreased channel sinuosity due to cutting of chute channels. Seven of the bars (B, C, D, F, G, H, and K) show evidence of chute channel reactivation during this time.

Effect of the Dam and Dam Removal

There are three sets of historical aerial photographs that approximately predate the Coho Dam. The two time intervals bracketed by those sets of photographs show that, prior to the construction of the dam, the study area was characterized by alternating sedimentation and erosion zones which moved downstream as one or several of sediment waves. In this dynamic environment, the bedform centroids remained approximately the same thalweg-path distance upstream from a fixed point, in other words channel sinuosity was relatively constant.

The life history of the Coho Dam is bracketed by five sets of historical aerial photographs, creating four time intervals. For individual bars, there was a complex response to the construction of the dam depending upon the time interval of reference. Over the long-term (1969-2002), it is evident most bars increased in size. This is attributed to the reduced transport capacity in the study reach due to the construction of the dam and reduction of slope upstream of the reservoir. However, over the short-term many individual bars fluctuated in size such as the unusually large growth rate of bar J during 1988-95. Both pre-dam and post-dam there is a pattern of depositional and erosional zones comprised of groups of bars (see the above discussion of sediment waves), but during the history of the dam this was replaced by a more diffuse pattern of alternate bars growing or decaying. We interpret this pattern to show transient disequilibrium effects that the growth or decay of individual bars can have on adjacent bars during a period of hydraulic adjustment to the presence of the dam. Finally, it should be noted that while individual bars fluctuated in size over the short-term, the sinuosity of the channel continually increased, as indicated by the increased thalweg-path distance from the centroid of each bar to a fixed location (Figure 7).

The effects of dam removal are less well understood because they are based upon a single time interval. The study reach appears to be reorganized into depositional and erosional zones consisting of groups of bars, in other words it appears that modification and removal of the dam resulted in rejuvenated translation of sediment waves through the study reach. The downstream passage of sedimentation and erosion zones resulted in cutting of chutes, shortening of thalweg-path length from each bar centroid to a fixed point downstream, and hence the downstream shift in bedform centroids (Figure 7).

Summary

This study has demonstrated the following. First, GIS and remote sensing are tools that can be applied to study the behavior of individual bedforms to interpret changes in important geomorphic parameters over time, specifically the size, shape, and position of bars and channel sinuosity. Second, in some cases there exist a historical database of aerial photographs that span the life history of dams and permit an analysis of pre-dam and post-dam geomorphic impacts. Third, the pre-dam condition of the Huron River through the study area consisted of alternating sedimentation and erosion zones, similar to many natural rivers observed elsewhere (e.g., Desloges and Church, 1987). Fourth, the downstream migration of these sedimentation and erosion zones over time can be interpreted as the downstream translation of a sediment wave. Fifth, the construction of the dam reduced the gradients and decreased the transport capacity upstream of the reservoir, resulting in no net downstream translation of the sediment wave. Sixth, the sediment wave subsequently attenuated *in situ* by dispersion in response to erosion of the upstream reaches and deposition into the new reservoir. Shifting of sediment downstream was marked by local episodes of bar growth, which increased the thalweg-path distance between the bedform centroids and a fixed point downstream. Seventh, removal of the dam in 2002 rejuvenated translation of sediment waves through the study reach. The downstream shift of sedimentation and erosion zones cut chutes and eroded the inner-bank margin of bars, resulting in a downstream shift in bedform centroids with respect to thalweg-path distance to a fixed point downstream.

Finally, this study demonstrates the dynamic quality of fluvial bedforms upstream of even a fairly small dam. Changes in channel pattern and sinuosity are important constraints on the hydrologic system. The responses of channel reaches upstream of the reservoir should become an important part of the discussion about the impact of dams, dam removals, and river restoration.

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