Prediction of Stage, Bathymetry, and Riparian Vegetation of the Lower Olentangy River After Removal of the Fifth Avenue Dam

Alexandra C. Naegele
School of Environment and Natural Resources

Advisor:

William J. Mitsch
Professor**,** School of Environment and Natural Resources
Director, Olentangy River Wetland Research Park
352 W. Dodridge Street
Columbus, Ohio 43202

Committee Members:

William J. Mitsch
Roger Williams
Li Zhang

Abstract

The Olentangy River is a third order stream as it passes through urban Columbus Ohio with an average flow of 191 ± 13 cfs and an annual peak flow of 2372 cfs (67.2 m^3/sec). As it passes through the city, it is impounded by several low-head dams. The 2-mile reservoir created upstream of a dam (referred to as the Fifth Avenue Dam) on the river and adjacent to The Ohio State University campus is currently in non-attainment of biological and ambient water quality standards. Planned river ecosystem restoration of this pool is based on the removal of the Fifth Avenue Dam, which would increase stream velocity and sediment transport, improving total water quality. This study looks at the relationships among flow, stage level, and current bathymetry of the Olentangy River to predict the bathymetric profile of the river upstream of the dam after it has been decommissioned and the vegetation that will result on new riparian areas. The flow of the river was calculated as a function of the river stage using a rating curve developed by the U.S. Geological Survey for the Olentangy River Wetland Research Park (ORWRP) and previous research at the ORWRP. Using the relationship between river stage and flow, we predicted changes in the bathymetry of the Lower Olentangy River. Additionally, we predicted an increase of riparian vegetation by 47 acres (for an 80% drop in stage), with expected riparian vegetation based on the growth pattern of emergent vegetation at similar locations along the river and at the Olentangy River Wetland Research Park.

Introduction

Within the past decade, the popularity of dam removal as a means of river restoration has increased dramatically. Although approximately 180 dams were removed in the United States in the 1990s, 30 were removed in 2001 alone (Mitsch and Jorgensen, 2004). Despite this rapid increase in numbers, very little scientific research has been done looking at the resulting hydrologic and ecological effects, and those that have are generally incomplete, looking at the process in fragments, rather than holistically (Mitsch and Jorgensen, 2004).

Goals and Objectives

The goal of this study is to predict the bathymetry and potential vegetation patterns in an 2-mile pool after a downstream dam removal in the lower Olentangy River in Columbus, Ohio. Only recently has research been conducted looking at the bathymetry of the Lower Olentangy River, which was involved with the Lower Olentangy River Ecosystem Restoration Project (Sanford et al., 2008). It is expected that removal of the Fifth Avenue Dam will significantly affect the physical characteristics of the water, and it will be important to be aware of the potential changes in river stage, stream velocity, temperature, and turbidity. This project has 3 objectives:

1. To provide a base map depicting the floor of the Olentangy River and the river hydroperiod after the dam removal. It is important for the city to anticipate of these changes since the river is, on occasion, polluted with raw sewage. Since the City of Columbus still uses a combined sewer system, the sewers overflow during major precipitation events, emptying the combined storm and sanitary sewage into the Olentangy River.

2. To predict vegetation communities that will develop in the drained pool after dam removal. The depth of the river and the bathymetry are important because they are major factors

that will determine what type of plant and animal life will be found in the pool after dam removal.

3. To predict human use of the resulting pool. The bathymetric profile and river height will be useful for planning the river's potential recreation, as both boating and fishing will be affected.

Effects of Dam Removal

Morphology:

The most notable effects immediately after dam removal is on the hydrology and river morphology (Pizzuto, 2002). Once the channel is affected by the dam removal, natural processes will act to reestablish equilibrium conditions, including changes in the width, depth, and alignment of the channel (Stanley and Doyle, 2002). The morphology is likely to complete a sequence of six stages of channel evolution, as being the standard for bringing the river back to equilibrium (Simon and Hupp, 1987), and the complete sequence of six stages occurs over several decades. In the first stage, the river is stable and at equilibrium, but it eventually becomes disturbed by human activity in the second stage. The third stage is characterized by rapid degradation, in which the channel deepens, and the bed slope flattens, causing instability and bank failure. Geomorphic processes upstream of the dam are dependent on the channel evolution after the incision into the sediment from the streamflow. Incision rates into the sediment upstream of the dam depend on both the dominant grain size (clay/silt, sand, gravel) and the relative height of the sediment. While the removal of clay, silt, and sand is process-driven, the incision of gravel is event-driven (Pizzuto, 2002). Evidence of the third stage is seen in a study that compared the physical and environmental effects of a riverine ecosystem before and after the removal of a low-head dam in the Baraboo River in Wisconsin. Immediately following dam removal, the slope of the bank increased drastically and the river narrowed and deepened, downcutting into river sediments. It is likely that this morphology would have persisted once vegetation established and physical stabilization of the banks occurred, but a flood in June increased the width of the river, seeming to have permanently affected the channel morphology (Stanley et al., 2002). In another study, degradation occurred upstream of the dam, though there was no change in the channel width at any point (Cheng and Granata, 2007). This degradation causes the channel to widen, which in turn results in aggradation (fourth and fifth stages respectively). Since it is possible that aggradation rates may be only half that of degradation, the river will never reach its original state, but will eventually come to a state of quasi-equilibrium seen in the sixth and final stage. An important factor that affects the river is the floodplain, which is a function of the amount of aggradation (deposition of alluvial sediments), and degradation (downcutting of surface geology) (Mitsch and Jorgensen, 2004). Exposed sediment lateral to the forming channel dries and, over time, becomes more physically stable, giving rise to a new floodplain (Stanley and Doyle, 2003). Sediment transport downstream could impact the geomorphology at the reach scale, including destruction of pools and riffles, burial of coarse-grained riffles by finer-grained sediment, and modification of bedforms and armor. Downstream, sediment transport is likely to be a function of translation, dispersion, or a combination of both processes (Pizutto, 2002).

Vegetation:

Riparian ecosystems are interrelated with rivers in riverine ecosystems, and can be found wherever at least occasional flooding of rivers occurs (Mitsch and Jorgensen, 2004). Dam removal may change aspects of the hydrological regime that structure riparian vegetation, including flood and low- flow regimes and associated water table dynamics, but riparian vegetation can stabilize sediments in former reservoir pools, perhaps reducing downstream sediment transport that can harm aquatic ecosystems (Shafroth et al., 2002). Although floods can certainly result in the destruction or stressing of vegetation, the effects are largely dependent on species tolerance. However, floods play at least three roles in the establishment and survival of riparian plants. First, most riparian plants germinate in alluvium that is deposited during floods. These fresh deposits provide sites for colonization, and the energy conditions of the floods determine the texture of the new substrate. Second, floods may create colonization sites by destroying pre-existing vegetation. Third, the occurrence or lack of floods subsequent to germination may determine whether seedlings survive to maturity. In some cases, floods may also play a significant role in dispersing propagules to colonization sites. Additionally, disturbance by floods can also affect biodiversity, as species richness in some watersheds is greatest where steep valley floor gradients allow for high-energy flood.

Although flooding strongly affects the riparian vegetation, strong feedback interaction exists between the two (Bendix and Hupp, 2000). Vegetation between a water body and the surrounding uplands is dominantly structured by the hydrologic gradient, with differences in the duration, frequency, and timing of inundation (hydroperiod) (Shafroth et al., 2002). Hydrological impacts include mechanical damage, saturation and seed transport, and geomorphological impacts involve the destruction and creation of substrate (Bendix and Hupp, 2000). Upstream, there will initially be a transition phase involving colonization of extensive bare areas or mud flats that are uncovered as water stages decline with the draining of the reservoir, and this substrate may favor non-native plants (Shafroth et al., 2002). For example, in the first year after creation, the unplanted wetland at the ORWRP contained many tree seedlings and mudflat species, and most of the colonizing vegetation in the first year was facultative, that is, capable of growing in both uplands and wetlands (Weihe and Mitsch, 1995). Vegetative growth can be observed in former reservoir areas during the first growing season after removal; the first colonizers are usually fast growing forbs and grasses, followed later by longer lived species, including riparian trees (Stanley and Doyle, 2003). Downstream, dam removal could restore natural hydrologic regimes (less variable than unregulated flow), which can contribute to the rehabilitation of native plant communities. Ultimately, a fundamental goal of any attempt to actively reestablish self-sustaining riparian vegetation should be to restore or reestablish key physical processes such as natural flow variability and channel change. Such physical processes integrate terrestrial and aquatic elements of the watershed, producing spatially and temporally distinctive patterns of vegetation establishment (Shafroth et al., 2002).

Methods

Study Area

The Olentangy River is a third order stream in Central Ohio and drains a 943-square-mile watershed (Ohio EPA, 2006). Currently, the Lower Olentangy River, characterized by its urban location in Franklin County, is impacted by combined and sanitary sewer overflows, urban runoff, and low head dams that result in high nutrient and pathogen loads, poor habitat, siltation, seasonally low dissolved oxygen concentrations and elevated stream discharges (Ohio EPA, 2006). Consequently, the 2-mile reservoir created adjacent to The Ohio State University campus and upstream of the Fifth Avenue Dam (Figure 1) is currently in non-attainment of biological and ambient water quality standards. The dam, which is 8-feet high and 470-feet wide (Figure 2), was originally created to supply cooling water for the University's McCracken Power Plant; that water use is no longer required. Now, the river is a slow-moving reservoir with impaired water quality, resulting in a poor aquatic habitat (U.S. Army Corps of Engineers, 2006).

Streamflow

Streamflow was determined from readings taken manually twice per day at the staff gage located at the Clinton Park weir by Olentangy River Wetland Research Park (ORWRP) staff, students and volunteers from 1994 through 2009. The staff gauge is located at the northwestern corner of the ORWRP, since the experimental wetlands were created on March 4, 1994. Although the readings were meant to be recorded twice daily, certain circumstances such as breaks between quarters prevented monitoring, resulting in gaps of a day or more in the readings. As a result, the two-a-day readings through December 31, 2009 were interpolated to give four-hour readings. These four-hour readings were then averaged over each month to yield a daily stage level. Flow was calculated as a function of the staff gage reading at the upstream low-head dam on the Olentangy River at the ORWRP using the polynomial relationship based on stage and discharge data determined by the U.S. Geological Survey (USGS) for the ORWRP (Mitsch, 1996):

$$\log_{10}Q = -8297.686 + 20553.497(\log_{10}x) - 16968.005(\log_{10}x)^2 + 4670.576(\log_{10}x)^3$$

where, x= staff gage reading at Clinton Park weir (ft), and Q= Olentangy River flow (cfs).

This relationship is only accurate for staff gage readings less than or equal to 17 ft; otherwise the predicted flows are too high (Mitsch, 1996). This relationship was created for the original staff gage, and as a result, readings from the new staff gage (installed in April of 2006) were corrected to account for the 13.5 ft decrease. A linear relationship was extrapolated from the previous model, such that for staff gage readings greater than 17 ft:

$$Q = 3516.286 + 2131.7(x-17)$$

Flooding Patterns

After daily streamflow was calculated, flooding events were easily observable and the peak flow for each water year (from October 1 to September 30) was determined. Estimates of flood flows of given recurrence intervals are needed for design of hydraulic structures and floodplain management. PeakFQ, a USGS-developed program for annual flood-frequency analysis (USGS, 2006), used 14 years of peak flow data (1994 to 2007) to determine a log-Pearson Type III distribution, which describes the occurrence frequencies of peak discharges. As implemented in program PeakFQ, the Pearson Type III frequency distribution is fit to the logarithms of instantaneous annual peak flows. The parameters of the Pearson Type III frequency curve are estimated by the logarithmic sample moments (mean, standard deviation, and coefficient of skewness), with adjustments for low outliers, high outliers, historic peaks, and generalized skew (USGS, 2006). The program used the location of the USGS monitoring site 03226800 (Olentangy River near Worthington) to determine the skew, though the flow data used for the distribution was measured at the Clinton Park site. The USGS Worthington monitoring site is approximately six miles upstream of the Clinton Park weir.

To compare the streamflow from the USGS Worthington monitoring site and the Clinton Park weir site, average daily streamflow values were plotted against each other. All pairs of data in which the flow measured at the Worthington site was greater than the flow measured at the Clinton Park site were disregarded. The Worthington streamflow data was retrieved from the USGS website, where the data are publicly available. At this monitoring site, daily values were available beginning October 1, 1996 through December 27, 2009, and so this time period defined the period of comparison.

Projected Hydrology

For this project, the ORWRP installed a staff gage in the spring of 2008 on the walking bridge near the Drake Union to measure the river stage. To determine the patterns of the stage of the river, it was necessary to find a relationship between the stage of the pool and the stage at the Clinton Park weir, and to know the elevations of each staff gage. The elevations of the staff gages were surveyed by Myers Surveying on May 19, 2010. The base (reading =0.00) of the current Clinton Park weir gage is 722.29 feet above mean sea level (FAMSL), and the base of the Drake Union gage is 708.54 FAMSL (NAVD 88 datum) (Table 2). Daily readings from the Drake Union staff gage were plotted against those from the Clinton Park weir site to determine a relationship between the stages of both pools. Once this relationship was calculated, the stage of the inundated pool between the Fifth Avenue Dam and Lane Avenue (lower half of the pool upstream of the dam) for the median flow was projected onto a bathymetric map of the river, produced by EMH&T and obtained from Sasaki Associates, which is measured in 1-ft increments. The bathymetric survey uses the NAD 83 datum, which in Ohio is the State Plane-South coordinate system, and is compatible with the NAVD 88 vertical datum. The NAD 83 geodetic datum was used by ESRI ArcGIS 9.0 to analyze the bathymetric map. ESRI ArcGIS 9.0 is a geographic information system software package, and is built around the geodatabase, which uses an object-relational database approach for storing spatial data. ArcGIS was used to predict the bathymetry of the river after dam removal and the surface area of the pool over a range of elevations, each corresponding to a specific percentage decrease of the river stage. Areas were measured by cutting the map along its contours and weighing the pieces to a precision of 0.0001 gram. The weight of a known area was used as a reference. Because of uncertainty of how the gradient of the river channel affects the slope of the surface water, of both the current reservoir and the restored river, several approaches were used to determine the surface area. The first approach assumed that the water surface would be at a constant elevation throughout the entire pool. The second approach used a 3.27 foot per mile gradient of the river as described by FLOW (2003). Because of the 1-ft contour interval of the bathymetric survey, the stretch of the river from the dam to Lane Avenue was divided into several segments, and the surface area was calculated individually for each segment at increasing elevations from downstream to upstream. A third approach used the average of these two measures, since the slope will change depending on the flow of the river. These predicted surface areas were compared to the current surface area, to calculate the percentage of surface area maintained after dam removal.

This overall method only determined the surface area for the stretch of the river between the Fifth Avenue Dam and Lane Avenue. To estimate the surface area of the entire pool, the percentages (only for sloped and average surface areas) were used in combination with the surface area for the entire pool.

Riparian Vegetation

The final phase of the river ecosystem restoration predictions includes the biotic factor of the ecosystem. Staff gage readings (indicating both flow and elevation) over a 15-year period (1995-2009) were analyzed to determine the distribution of inundated elevations. Percentiles were calculated each year, corresponding with 25% and 40% inundation durations, and then averaged over the 15-year period. These elevations were then applied to the projection of the predicted hydrology to determine the areas of riparian vegetation growth. Elevations flooded at a 25-40% duration, generally characterizing channel bars, were expected to be colonized primarily by herbaceous aquatic plants (Hupp and Osterkamp, 1996). Elevations flooded at a duration of less than 25% were expected to support vegetation dominated by woody species, and eventually mature to a riparian bottomland forest.

The expected species were based on the succession of vegetation along the experimental wetlands at the ORWRP, where a mature hardwood bottomland hardwood forest is 15-years into developing in a mudflat zone that is subject to periodic flooding and groundwater near the surface. Additionally, a bulletin on native Ohio plant species was referenced to predict which plant species would grow in the riparian area (Sheaffer and Rose, 1998).

Results and Discussion

River Description and Data Analysis

For the past 16 years (1994-2009), there has generally been an annual high flow in the Olentangy River at the ORWRP in the spring out of several flood events, which result from high precipitation events and sometimes spring thawing, though flood events are distributed throughout the year (Figure 3).

Flows from the Clinton Park weir, in comparison to those from the Worthington site, were not as similar as expected (Figure 4), and can be approximated by the following linear relationship ($R^2 = 0.84$):

$$Q_{cp} = 1.16\ Q_w + 164$$

where

Q_w = streamflow at the Worthington site, and

Q_{cp} = streamflow at the Clinton Park weir.

It is important to note that this relationship only accounts for the set of data pairs in which the Clinton Park site measured a flow higher than that measured at the Worthington site. For data pairs in which the Worthington site measured a higher flow, the Worthington flow value was considered incorrect and the pair was eliminated from the regression. This modification to the dataset was made to account for the expectation that the more downstream site should have a higher flow. Although there are no major tributaries that flow into the river between the two sites, runoff from the urban watershed should have led to increased streamflow. Additionally, as the river approaches Columbus, the area in the watershed becomes more urban, and an increase of impermeable surfaces contributes to increased runoff.

The staff gage readings near the Drake Union on campus corresponded to those from the Clinton Park weir as follows ($R^2 = 0.63$):

$$L_{DU} = 0.66\ L_{CP} + 0.19$$

where

L_{CP} = the stage at the Clinton Park weir (ft) and

L_{DU} = the stage near the Drake Union (ft).

This equation best represents the relationship for low and middle range flows. For high flows, this relationship is less reliable because of the lack of data, a consequence of the rarity of flooding.

The median flow of 191 ± 13 cfs at the Clinton Park weir corresponded to a staff gage reading of 0.79 feet. The median was used instead of the mean to eliminate skew resulting from extremely high flows.

<u>Flooding Patterns</u>

The Log Pearson Type III Distribution (Figure 5), commonly used in hydrologic studies, is similar to the normal distribution, however it includes skew in the calculation, in addition to mean and standard deviation and is commonly used in extreme event hydrologic analysis (Chow 1959). Lower and upper confidence intervals (±95%) are also illustrated. Each probability represents the chance that a flood event reaching a given streamflow will occur in one year. During the 16-year span of data collection, the five-year flood occurred twice, the two-year flood occurred ten times, and the ten-year (8,845 cfs) and one-hundred-year (12,576 cfs) floods each occurred once. Both the ten-year and one-hundred-year floods occurred during the summer of 1995 (Mitsch, 1996). The summer peak flow events indicate that the flooding was a result of urbanization.

Projected Hydrology

Because of the immaturity of dam removal as a research field and a dearth of studies comparing the environmental conditions before and after dam removal and specifically, those examining the drop in river stage, there was no basis for which to create an accurate model, and many approaches were originally considered. One option considered a water drop corresponding with the height of the dam (8 ft), which would have lowered the water level to the riverbed in the upstream parts of the pool. Although this is clearly not what would happen, we were unable to decide how the water would fill the pools, and so this did not seem like a feasible approach. A second method considered to predict the bathymetry of the restored river was to use a reference reach. The Olentangy River below the Fifth Avenue Dam could be used as a reference site because it shares the same channel gradient as the river upstream of the dam, while maintaining a free-flowing hydrologic regime. In this case, the width of the restored river channel is expected to be similar to that of the downstream reference reach. Projecting the expected channel width to the bathymetric map would yield the stage and show newly exposed channel bed. A third approach we considered involved the creation of hydraulic model. However, because there has been so little research looking at the effects of dam removal on hydrology, we were not sure how to proceed with the creation of such a model. We consulted with the U.S Army Corps of Engineers (USACE) to see if a hydraulic model had been developed. The USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS), used to perform one-dimensional flow modeling, had been run to predict the post-removal hydrology. Although the model was run for this scenario, because HEC-RAS is better suited for modeling larger flows (i.e. those corresponding to 100, 200, 500+ year flood recurrence intervals), the outcome was not very applicable to the prediction of the commonly observed flows. HEC-RAS was not recommended as a suitable model for this situation (Jeff Zylland (U.S. Army Corps of Engineers' Environmental Specialist assigned to the Fifth Avenue Dam Removal), personal communication, April 30, 2010). It was suggested that a comparison to a downstream reference reach, characterized by a narrower channel width, would better predict the hydrology. Although this was considered, it was finally decided that the surface area of the pool over a range of elevations, each corresponding to a specific percentage decrease of the river stage, would be determined.

Once the hydrology was predicted, the corresponding bathymetry prediction was a simple projection, indicating the location and extent of exposure of the riverbed. It is well known that dam removal can have considerable effects on the sediment transport and geomorphology of the river, though neither was considered in this prediction.

Figure 6a shows the bathymetry of the stream pool from the Fifth Avenue Dam to Lane Avenue. Under current conditions, the channel is entirely flooded at median flow. The shaded areas in Figures 6b and 6c show, respectively, the current flooded area at median flow and the area that can be expected to remain submerged if the stage is reduced by 80%. A high stage reduction (up to 80%) dramatically changes the flooded channel area or width in most areas (Table 3).

Riparian Vegetation

By applying the current hydrology pattern to the bathymetric projection, it is shown that the areas of the lower and higher riparian areas will change. The elevations of these two distinct riparian zones will depend on the percent stage reduction after the dam is removed. The area of the lower riparian area will fluctuate depending on the stage drop (Table 4), but the forested, upper riparian area (includes all elevations with less than 25% inundation) increases as the stage drops because it is measured cumulatively (Table 5). With a stage reduction of 80% after dam removal, an increase of 47 acres of riparian areas can be expected. Once exposed, the lower zone will be a mudflat, and herbaceous species will be the primary colonizers. These species may include, but are not limited to: *Asclepias incarnata, Juncus effusus, Aster* spp., all of which are either native Ohio perrenials suited for wet soils or are among the species found in the riparian zone at the ORWRP. Additionally, because this substrate may favor invasive species, *Lythrum salicaria* and *Lonicera mackii* may become dominant species in the lower and upper vegetation zones, respectively. In the higher, less-frequently flooded zone, colonization will be slower and will favor woody species. The initial colonization will likely be by *Populus deltoides*, and *Salix nigra*, followed by *Acer negundo* and *Platanus occidentalis*, and will eventually develop into a bottomland hardwood forest (Noon and Mitsch, 2008).

Conclusions

It is rare that such an extensive collection of hydrology data is available in a comprehensive dam removal study. The hydrology data over a 16-year period was valuable in attempting to predict the effects of dam removal on the stage of the lower Olentangy River. However, a major obstacle encountered during this project was the lack of research at other dam removal sites examining the effects of dam removal. Of the studies conducted in this field, the vast majority fail to provide a before and after comparison, and many look not at the change in hydrology, but at the effects on sedimentation, geomorphology, or fish and invertebrate species. Because of the lack of similar studies, there was no strong observational data to serve as the basis of a model to determine how much the water level would drop. Therefore, a range of outcomes was predicted, several of which match the characteristics of reference reaches downstream. Although this method does not provide a single precise prediction, the range is much for suitable for ecosystem restoration projects, and allows for flexibility and self-design. Using this range of predictions, we were able to predict a maximum increase in riparian area of 47 acres, and the forested riparian vegetation areas will create new bird and wildlife habitat. Additionally, the data analysis of the current hydrologic patterns will serve as a good point of comparison for continued research post-dam removal.

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References

Bendix, J. and Hupp, C. R. 2000. Hydrological and geomorphological impacts on riparian plant communities. *Hydrological Processes*, 14: 2977–2990

Cheng, F. and Granata, T. 2007. Sediment transport and channel adjustments associated with dam removal: Field observations. *Water Resource Res*. 43: W03444.

Chow, V.T. 1959. *Open channel hydraulics*. New York, NY: McGraw-Hill.

Doyle, M.W., Luebke, M.A., Marshall, D.W. and Stanley, E.H. 2002. Short-term changes in channel form and macro invertebrate communities following low-head dam removal. *Journal of the North American Benthological Society,* 21:172-187.

Flynn, K.M., Kirby, W.H. and Hummel, P.R. 2006. User's Manual for Program PeakFQ, Annual Flood-Frequency Analysis Using Bulletin 17B Guidelines. Reston, VA: U.S. Geological Survey.

Friends of the Lower Olentangy Watershed (FLOW). 2003. Geology of the Olentangy River Watershed. In *A snapshot: The state of the Lower Olentangy Watersheds in 2001: Lower Olentangy River watershed inventory* (7-22). Columbus, OH.

Hupp, C.R. and Osterkamp, W.R., 1996. Riparian vegetation and fluvial geomorphic processes. *Geomorphology*, 14(4): 277.

Mitsch, W.J. 1996. Olentangy River streamflow and flooding in 1995. *Olentangy River Wetland Research Park at The Ohio State University Annual Report 1995*. 29-35.

Mitsch, W.J. and Jorgensen, S.E. 2004. *Ecological Engineering and Ecosystem Restoration*. Hoboken: John Wiley & Sons, Inc.

Noon, M.L. and Mitsch, W.J. 2008, May 14. *Vegetation analysis of a bottomland hardwood forested wetland upstream of a dam prior to removal*. Poster presented at the Denman Undergraduate Research Forum.

Ohio EPA. 2006. *Olentangy River Watershed Draft TMDL Report.*

Pizzuto, J. E. 2002. Effects of dam removal on river form and process. *Bioscience* 52:683–692.

Sanford, D., Lowry, S. and Merry, C. 2008, May 14. *Elevation Analysis of the Olentangy River Corridor using LiDAR Imagery and Bathymetric Modeling*. Poster presented at the Denman Undergraduate Research Forum.

Sheaffer, C. and Rose, M.A. 1998. *The native plants of Ohio*. Columbus: Department of Horticulture, The Ohio State University.

Simon, A. and Hupp, C.R. 1987. Geomorphic and vegetative recovery processes along modified Tennessee streams: An interdisciplinary approach to disturbed fluvial systems. Proceedings of the *Forest Hydrology and Watershed Management Symposium*, Vancouver, August 1987. 167:251-261.

Stanley, E. H. and Doyle, W. M. 2003. Trading off: the ecological effects of dam removal. *Frontiers in Ecology and the Environment*: 1(1): 15-22.

U.S. Army Corps of Engineers. 2006. *Preliminary Restoration Plan For The Fifth Avenue Dam Removal/Modification Ecosystem Restoration Project, Columbus, OH*. Huntington, WV: USACOE, Huntington District.

Weihe, P.E. Mitsch, W.J. 1995. Macrophyte colonization of experimental wetlands at Olentangy River Wetland Research Park in 1994. *Olentangy River Wetland Research Park at The Ohio State University Annual Report 1994*, 90-97.

Table 1. Flood events with corresponding recurrence interval for lower Olentangy River at Clinton Park Weir at ORWRP.

Recurrence Interval (years)	Flow (cfs)	Flow (m^3/sec)
1	2372	67.2
2	5659	160
5	7150	202
10	8119	230
100	11390	322
200	12490	354

Table 2. Elevations at the base (0.00 ft) of the two staff gages used in determining the hydroperiod of the pool upstream of the Fifth Avenue Dam.

Location of Staff Gage	Elevation (FAMSL)
Clinton Park weir at ORWRP	722.29
Drake Union on OSU campus	708.54

Table 3. Surface areas of flooded area for a range of predictions dependent on stage drop.

% Stage Reduction		Fifth Ave. Dam to Lane Ave.			Fifth Avenue Dam to Dodridge Dam*
		Area (acre)	Area Decrease (acre)	% of Total Channel Area	Area (acre)
Current (0)	slope	37	0	78%	54
	average	38	0	80%	56
	flat	38	0	80%	56
20	slope	28	9	59%	41
	average	29	9	61%	43
	flat	30	8	63%	**
30-40	slope	20	17	42%	29
	average	21	17	44%	31
	flat	23	15	49%	**
50-60	slope	12	25	25%	18
	average	14	24	30%	21
	flat	17	21	36%	**
70-80	slope	5	32	11%	7
	average	8	30	17%	12
	flat	11	27	23%	**

**surface area was estimated using a percentage*

***not applicable*

Table 4. Surface areas of herbaceous vegetation/mudflat area for a range of predictions dependent on stage drop.

% Stage Reduction		Fifth Ave. Dam to Lane Ave.		Fifth Avenue Dam to Dodridge Dam*
		Area (acre)	% of Total Channel Area	Area (acre)
Current (0)	slope	5	11%	7
	average	4	8%	6
	flat	4	8%	6
20	slope	5	11%	7
	average	4	8%	6
	flat	4	8%	**
30-40	slope	4	8%	6
	average	4	8%	6
	flat	3	6%	**
50-60	slope	4	8%	6
	average	3	6%	4
	flat	3	6%	**
70-80	slope	4	8%	6
	average	3	6%	4
	flat	3	6%	**

*surface area was estimated using a percentage

**not applicable

Table 5. Surface areas of forested riparian vegetation areas for a range of predictions dependent on stage drop.

% Stage Reduction		Fifth Ave. Dam to Lane Ave.			Fifth Avenue Dam to Dodridge Dam*
		Area (acre)	Change (acre)	% of Total Channel Area	Area (acre)
Current (0)	slope	6	0	13%	9
	average	5	0	11%	7
	flat	5	0	11%	7
20	slope	15	9	32%	22
	average	14	9	30%	21
	flat	13	8	27%	**
30-40	slope	24	18	51%	35
	average	23	18	49%	34
	flat	21	16	44%	**
50-60	slope	31	25	66%	46
	average	30	25	63%	44
	flat	28	23	59%	**
70-80	slope	39	33	83%	57
	average	36	31	76%	53
	flat	33	28	70%	**

**surface area was estimated using a percentage*

***not applicable*

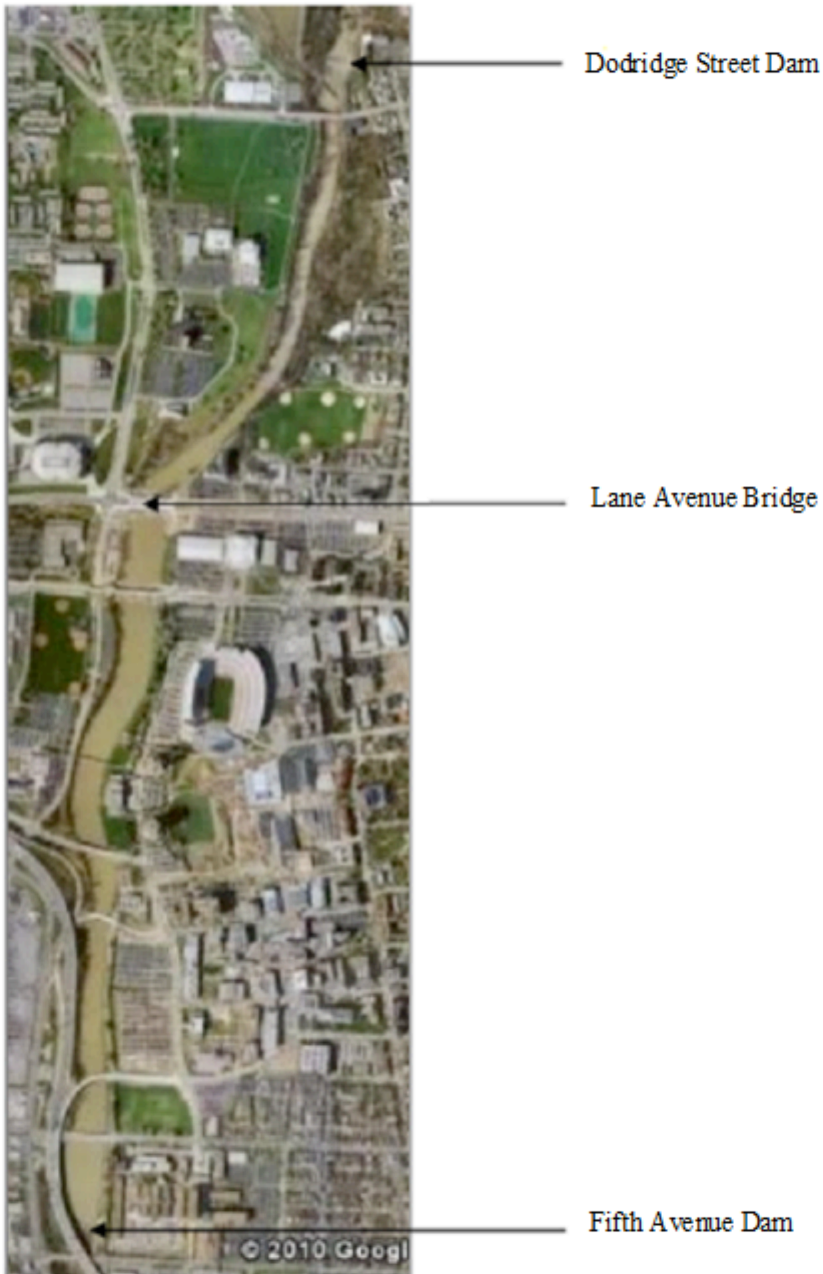

Figure 1. Map of the pool on the Olentangy River impounded by the Fifth Avenue Dam, bounded upstream by the Dodridge Street Dam.

Figure 2. Fifth Avenue Dam and a portion of the upstream created reservoir. (photograph by Alexandra Naegele)

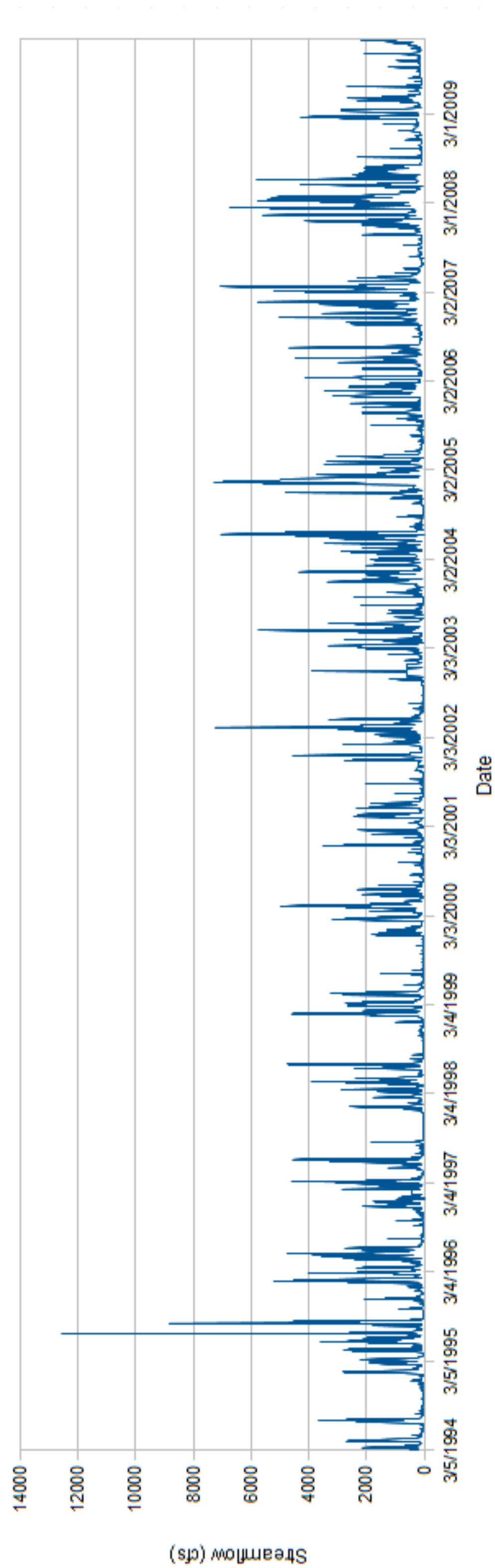

Figure 3. Olentangy River streamflow measured at the Clinton Park weir, ORWRP, 1994-2009.

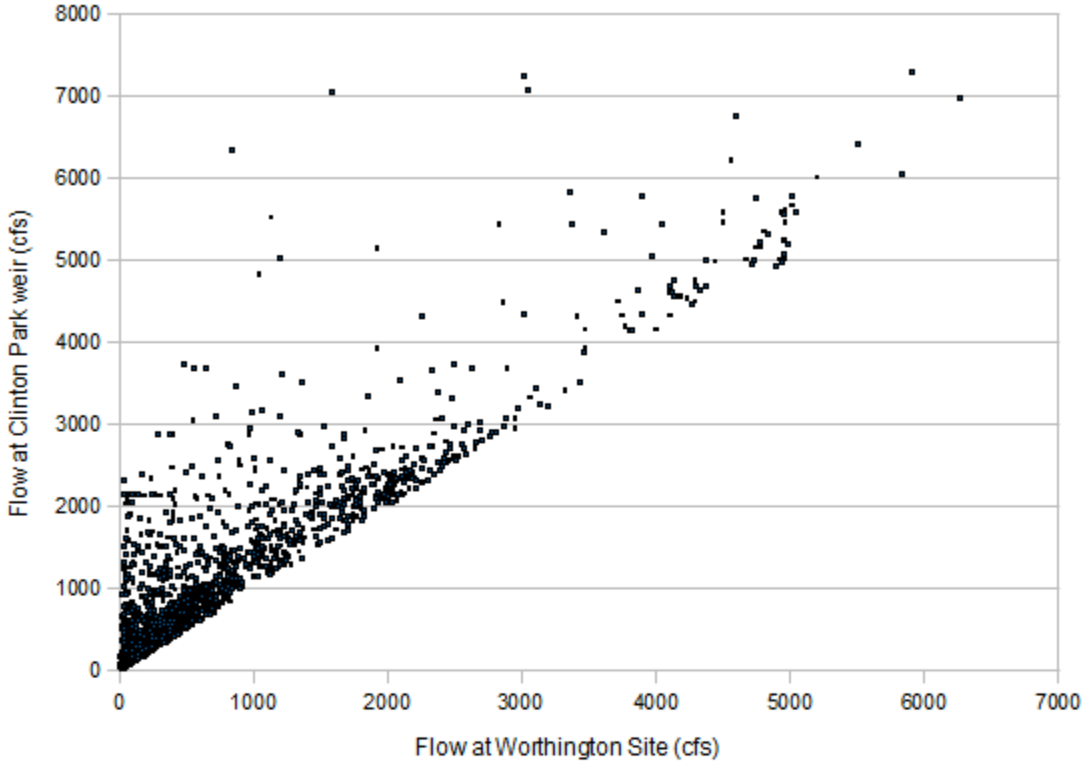

Figure 4. Comparison of average daily flow of the Lower Olentangy River measured at the USGS Worthington site and the Clinton Park weir, ORWRP.

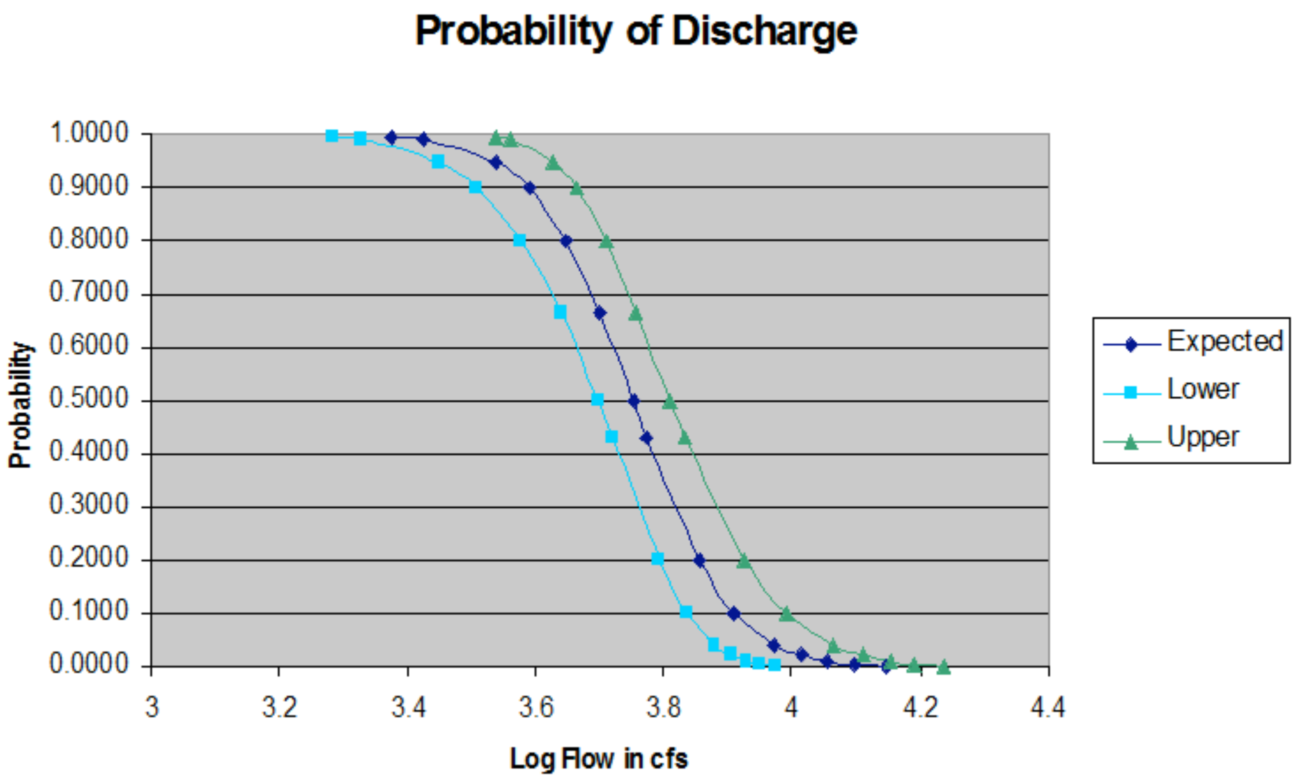

Figure 5. The occurrence probabilities of Olentangy River streamflows.

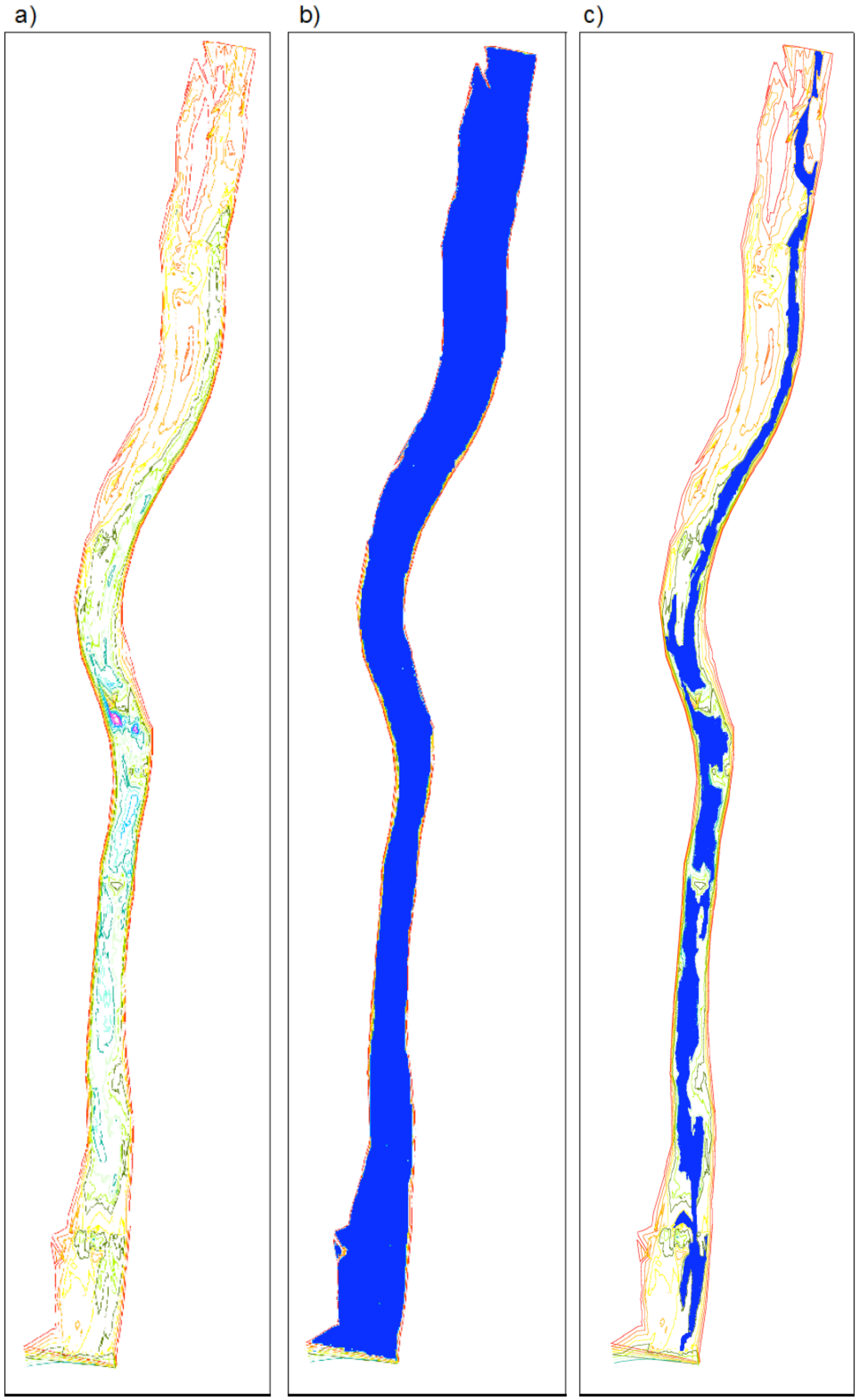

Figure 6 a) Stream channel bathymetry from Fifth Avenue Dam to Lane Avenue and comparison of the flooded area b) before and c) after dam removal to 80% stage reduction.