Linked geomorphic and ecological responses to river restoration: Influence of dam removal on river channel structure and fish assemblages

Final report

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Problem and Research Objectives

Over half of the large rivers in the world are affected by dams (Nilsson et al. 2005). As of 1999, 75,000 dams existed in the continental United States (Graf 1999), and Ohio contains thousands small dams <4 m in height. As these small and lowhead dams (< 7.5 m) age or their upstream reservoirs fill with sediment thus limiting their ability to store water, their removal is becoming an increasingly popular restoration method to reestablish connectivity of upstream and downstream streamflow, sediment regimes, and movement of organisms (Poff and Hart 2002). Yet despite the increasing trend towards dam removal there is an alarming lack of data relative to the ecological impacts of small dams and dam removal (Hart et al. 2002, Stanley and Doyle 2002, 2003). Dam removal results in upstream and downstream changes to both the channel morphology (the physical shape of channel) and the streamflow velocity regime, with subsequent consequences for the aquatic ecosystem including fish assemblages. However, the particular character of geomorphic change associated with dam removal and its subsequent influence on ecosystem processes remain poorly resolved. Thus, there is an urgent need to evaluate ecosystem consequences of dam removal (Gangloff 2013). In particular, fish communities represent an important component of aquatic ecosystems and play important social and economic roles in Ohio. Recreational fishing is a major revenue generator within the state. Therefore, how fish assemblages respond to dam removal reflects a critical knowledge gap in the burgeoning dam removal and river restoration research.

The removal of the 77 year-old "5th Avenue" lowhead dam (145-m long, 2.5-m high) on the Olentangy River presents an opportunity to investigate linked ecological-geomorphic consequences of dam removal as they relate to fish assemblage structure. In addition, these dams are located on rivers flowing through urban areas of Columbus, Ohio, thus providing additional opportunities to evaluate response within a land use that has not previously been evaluated in the context of dam removal.

The removal of the dam is part of the Lower Olentangy River Restoration project to restore the river channel to free-flowing conditions found upstream and downstream of the dam, reestablish floodplain features and vegetation, and develop pockets of wetlands. Because the restoration project is designed to accelerate long-term river change associated with dam removal (Figure 1), it creates an extraordinary scientific opportunity to monitor and investigate changes in linked ecological-geomorphic processes, particularly within the context of evaluating changes in the fish assemblage over time as well as overall evaluation of the function of a re-created river system.

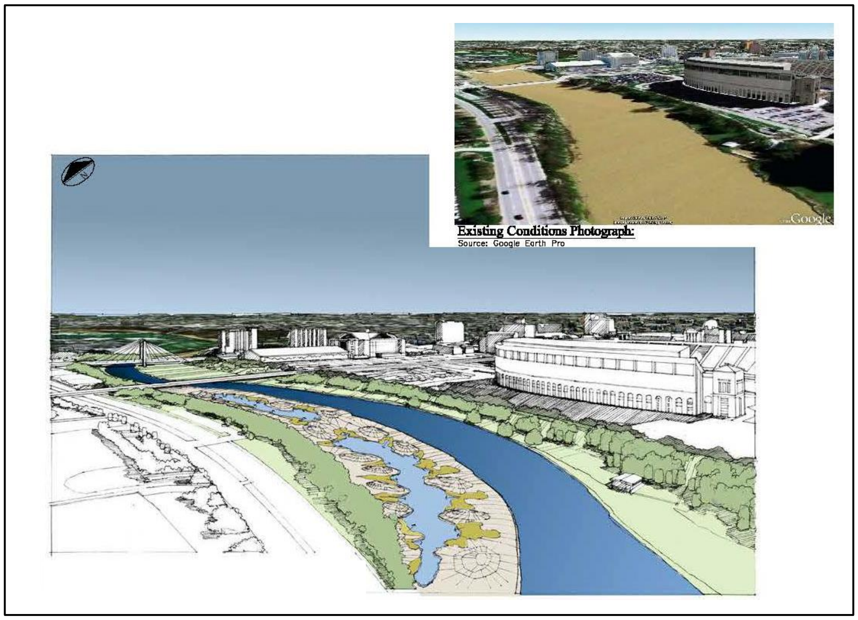

Figure 1. Proposed river corridor upstream of dam ~2 years after dam removal. Downstream of dam will not be actively restored. Dam was removed in August-September 2012.

Research Objectives

The overarching research objective was to investigate linked hydrogeomorphic and ecological short term response in a river following dam removal with a focus on fish community assemblages. We quantified geomorphic and ecological response following dam removal in (1) a downstream reach, (2) two upstream reaches, and tested that (3) riffle development following dam removal would be an important factor driving benthic macroinvertebrate and fish community responses. In addition, we also evaluated differences between restored and unrestored upstream reaches.

Methods

Study Design: The major component of the study followed a modified BACI (before-after, control-impact design) (Stewart-Oaten et al. 1986, Downes et al. 2002). Through ongoing research in the Olentangy River system (2010-present), Dr. Sullivan has "before" data relative to fish community assemblages from river reaches upstream and downstream of the 5th Avenue Dam, as well as at "control" sites. Pre-dam removal geomorphic data (Stantec, Columbus, OH) were available for use in this project. The control site represents an upstream (impounded) reach (OR1) of an intact lowhead dam of comparable size and age in the same study river system. Therefore, the proposed work focused on the "after" component of the design, and include data collection at study reaches upstream (two, one in unrestored [OR2] and one in restored [OR3] section) and downstream (one [OR4]) of the former 5th Avenue Dam, and one upstream of the intact "control" dam (OR1) (*n* = 4, Figure 2). Study reaches are ~300m long. All data were collected between 2013-2015.

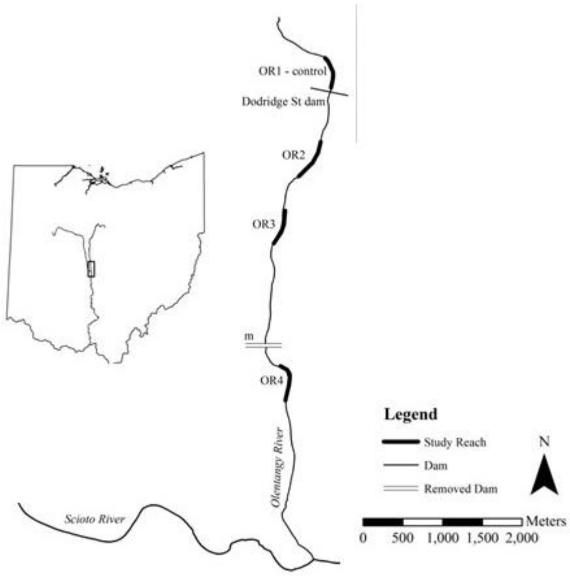

Figure 2. The Olentangy River study area in Columbus, Ohio. Picture for OR1-3 is facing upstream; picture for OR4 is in downstream direction. Figure adapted from (Dorobek et al. (2015).

For the second component of the study (3rd research objective), we surveyed five riffles at or upstream of the previous dam location, one riffle below the previous dam location, and one riffle downstream of an existing lowhead dam in the same river. Within each riffle, three quadrats were established at the top, middle, and bottom portions of the riffle to characterize representative microhabitats based on flow and substrate characteristics. Fish, benthic macroinvertebrate, chemical water-quality, substrate, and flow surveys were conducted within each quadrat at six time intervals: late spring (June), summer (August), and late fall of 2014; early spring (March), late spring (June), and summer (August) of 2015.

Geomorphic Data Collection: Changes in geomorphic complexity were quantitatively evaluated using repeated fine-resolution (0.5-m spacing array) bathymetric surveys in a grid array within each of the study reaches using an Acoustic Doppler Current Profiler (ADCP) to characterize variability in streambed elevation and quantify pool density. Digital Elevation Models (DEMs) were generated using krigging procedures that interpolate streambed topography based on this bathymetric data. Data collected during each bathymetric surveys were converted to a DEM, which was then differenced from DEMs of different survey periods to quantify change in streambed topography (Wheaton et al. 2015, Williams et al. 2015). In addition, changes in streambed sediment substrate size were evaluated through sieve analyses of bulk sediment samples at each study reach (Tullos and Wang 2014).

Sampling occurred at approximately 3-month intervals for a total of 4 sampling campaigns over the course of the year beginning in June 2013 and extending until September of 2015. Sampling included surveys of all study reaches using an Acoustic Doppler Current Profiler (ADCP) and streambed substrate sampling. The June 2014 sample period is one exception during which substrate sampling did not occur. The current data set include a range of six to eight hydrogeomorphic sample periods that roughly co-occur with biological data collection.

Biological Data Collection: Fish were sampled using a combination of standard boat- and backpack electrofishing (e.g., Brousseau et al. 2005, Kautza and Sullivan 2012) protocols. Individuals were identified to species, weighed (mg) and measured (mm). Species were classified by ecological and life-history traits following Frimpong and Angermeier (2009). Sampling occurred during the summer for each year of the study. See Dorobek et al. (2015) for additional details related to fish survey methodology. We also assessed relationships between riffle structure and benthic macroinvertebrate (using Surber samplers) and fish assemblages two years following the lowhead dam removal at six time intervals from late spring 2014 through summer 2015. In addition to the biological and geomorphic data, temperature, conductivity, dissolved oxygen (DO), and pH were measured using a YSI 650 MDS® (YSI Inc., Yellow Springs, Ohio) with attached 600R® sonde at each quadrat during each sampling period. In addition, one 500-ml water sample was collected from each riffle (at middle of the thalweg) during each sampling period for total mercury (Hg), total nitrogen (N), total phosphorus (P), nitrate (NO_3), phosphate (PO_4) and ammonia nitrogen plus phosphate (NH_4 + PO_4). The samples were stored at 4°C and sent for analysis at the The Ohio State University Service, Testing, and Research (STAR) Laboratory, Wooster, Ohio.

Data analysis: For objectives 1 and 2, hydrogeomorphic and fish-assemblage changes through time were first evaluated individually. For objective 3, water-chemistry and hydrogeomorphic data were used as potential predictors of biological responses.

Topographic changes in riverbed morphology, specifically the magnitude and spatial patterns of erosion and deposition were quantified using differencing of DEMs from individual survey periods. We also evaluated changes in streambed substrate character using the D_{50} and D_{84}, representing the grain size diameter of the 50th and 84th percentile substrate, respectively, and which typically are used to represent reach-scale hydraulic conditions of bedload sediment transport (e.g, the D_{84} grain size is generally the upper end clast size that is transported as bedload during relatively low flood magnitude events, for example the 2-year recurrence interval event).

Changes in fish assemblages were evaluated in terms of species richness (S), diversity (H') and evenness (E). Two-sample *t*-tests were conducted to test for potential differences in fish assemblage S, H', and E before and after dam removal, +1 and +2 years after dam removal, upstream and downstream of dam removal, and between the upstream restored and unrestored Olentangy River experimental reaches. We used Non-Metric Multidimensional Scaling (NMS) followed by analysis of similarities (ANOSIM) to test for differences in fish assemblage composition (1) between control and experimental reaches upstream from dams (e.g., OR1 and OR3), (2) before and after dam removal and, (3) between Olentangy River control and experimental reaches (e.g., OR1, OR2, OR3, OR4) across successive years following dam removal.

Subsequent analyses will include general linear models (GLM) and multivariate regression to relate continuous variable descriptors of hydrogeomorphic change (e.g., spatial variability in streamflow velocity, streambed bathymetry, pool and bedform spacing) to measures of changes in fish assemblage characterstics (e.g., density, community diversity, relative abundance of foraging groups).

For Objective 3, a mixture of analysis of variance (ANOVA), linear mixed models, regression, and Non-metric Multidimensional Scaling (NMS) were used.

Principal Findings

Hydrogeomorphology

We report on findings for the study period extending from June 2013 through September 2015.

Streamflow Conditions

Streamflow conditions during the study period were characterized by an overall larger mean annual discharge but relatively small peak flows (e.g., less than a flow of a 2 year recurrence interval) in the Olentangy River indicating relatively mild to moderate hydraulic conditions to carry out geomorphic change. Summers 2013-2015 experienced elevated streamflows for at least some portion of this season (Figure 3). In addition, Winter 2015 experienced lower than normal streamflow magnitudes.

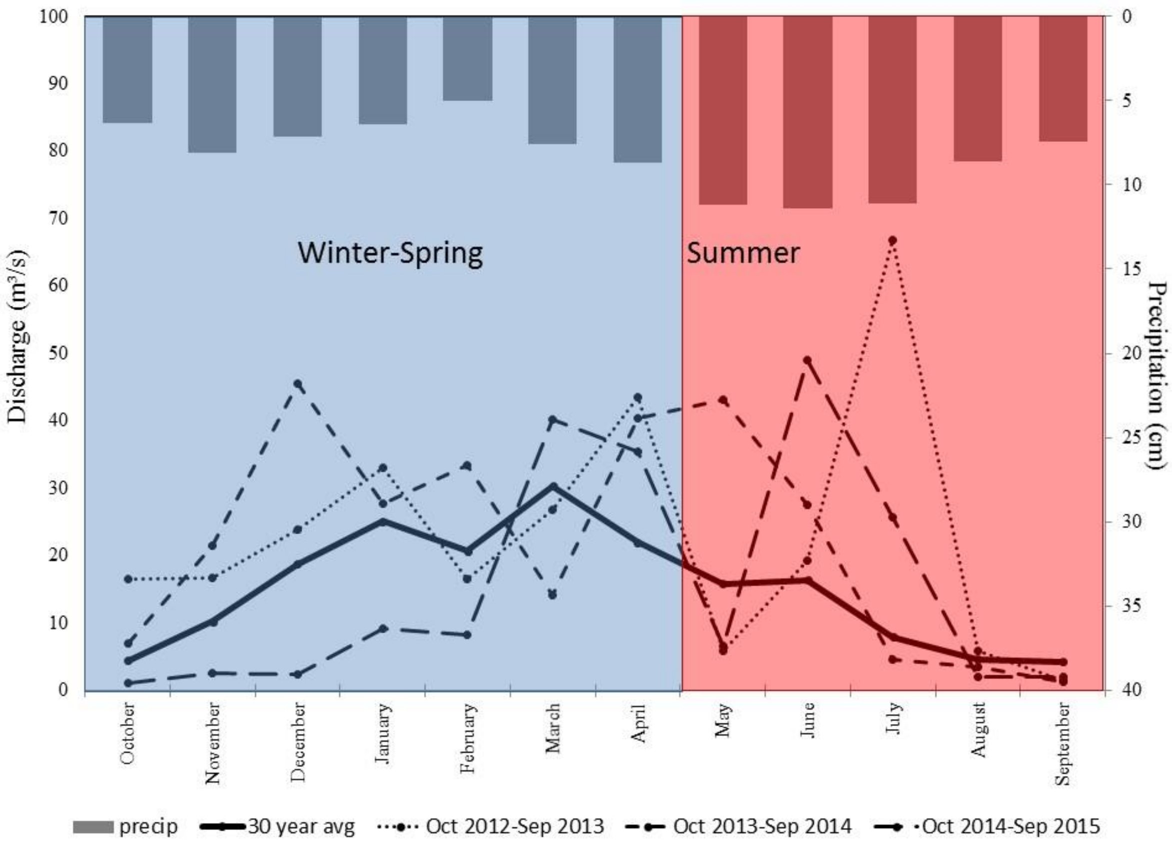

Figure 3. Monthly precipitation total and mean daily streamflow for each month over a 30-year period (1981-2010). Precipitation data are monthly normals from the NOAA National Centers for Environmental Information climate station at Columbus Ohio State University Airport, OH US. Discharge data is from USGS gage 03226800 Olentangy River near Worthington, OH monthly statistics from 1981-2010. Dashed lines are for Water Years 2013-

2015. Blue shading indicates winter and spring season (October-April) and summer (May-September), which approximately corresponds to the timing of the bathymetry surveys. Discrepancy between high summer precipitation normal values but lower normal streamflow values reflect regulation from upstream dams in the Olentangy River.

Changes in substrate composition

Changes in sediment grain size were observed over the study period (June 2013 – September 2015) and are reach specific. All study reaches are characterized by gravel (2 to 64mm) and finer material. Fines less than 2mm dominate all study sites with the exception of OR2 (the upstream, un-restored reached), which consistently had D_{50} larger than 2mm throughout the study period.

In general, reaches upstream and downstream of the removed dam are out of phase in terms of coarsening and fining behavior. In addition, coarsening and fining appear to correspond to different seasonal flows (Figure 4). In particular, coarsening in upstream reaches are concurrent with fining in the downstream reach and occur during winter and spring flows (e.g., Sep 2013-Apr 2014 and Sep 2014-June 2015). Conversely, fining in the upstream reaches are concurrent with coarsening in the downstream-of-the-removed dam reach and occur during summer flows (e.g., Apr 2014-Sep 2014 and Jun 2015-Aug2015). It is important to note that summertime flows involve several high flow events including the annual peak for the 2015 water year.

The abrupt increase in grain size diameter for the D_{84} at OR1 and OR4 in the second half of the study period beginning in September 2014 is attributed to changes in field sampling methods at these study sites (Figure 4). Prior to September 2014, sampling at OR1 had been limited to the right bank of the study reach but was extended to other coarser areas of the reach, notably a gravel bar located in the lower reach on river left. Similarly, the sample location at OR4 changed from one side of the river to the opposite side due to access issues, which was composed of coarser material. However, the out-of-phase pattern of OR4 relative to OR2 and OR3 occurs during consistent sampling methods beginning in September 2014 and therefore is interpreted as reflecting change in river sediment substrate character. Quantitative tests to evaluate change in sediment grain size through time will include comparison of observed change to background variability in grain size following Kibler et al. (2011). However, preliminary findings suggest that the upstream and downstream sites are behaving differently.

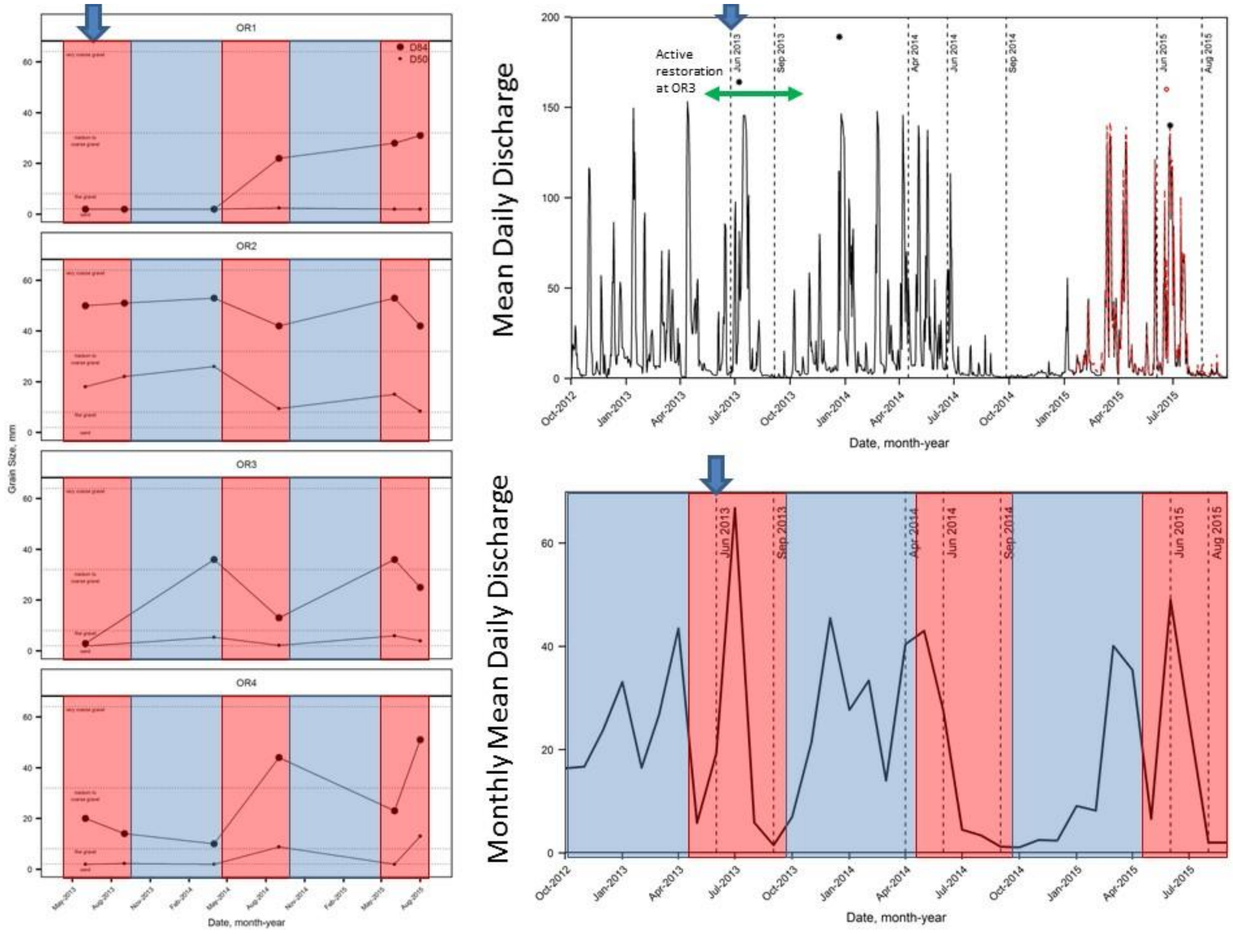

Figure 4. Changes in D50 and D84 at OR1-OR4 compared to streamflow for the study period. Left panels illustrate changes through time of D50a dn D84 clast sizes (mm). Top right panel illustrates mean daily discharge ($m^{-3}s^{-1}$) for the study period, vertical dashed lines indicate bathymetry studies. Bottom right panel illustrates mean daily discharge ($m^{-3}s^{-1}$) for each month for the study period. Red and blue shading reflect summer and winter-spring seasons, respectively. Blue arrow indicates start of first bathymetry and sediment data collection sampling period.

Changes in bathymetry

Analysis of bathymetric change is still in progress. DEMs have been created from bathymetric surveys and initial DEMs of difference have been generated. Initial analysis of DEMs of difference (DoD) indicate that observed changes in streambed bathymetry are reach specific. Changes in streambed bathymetry in the upstream unrestored reach, OR2, was concentrated along the thalweg, which occurs along the outside of a gentle bend on the left side of the river. Sequences of net erosion and net deposition occurred throughout the study period, and loosely correspond to seasonal patterns in streamflow discharge and substrate grainsize observed at this reach. In particular, net deposition tended to occur during winter/spring streamflows; net erosion corresponded to summer streamflows. These findings suggest that winter and spring streamflows deposit new material within this reach, which may also be the reason for observed coarsening of streambed substrate during this time period. Observed net erosion of the streambed and concurrent fining of the streambed substrate during summertime flows was unexpected, since erosion and coarsening tend to be linked, suggesting that observed changes were a result of upstream streamflow and sediment delivery and not downstream dam removal. Collectively, the erosion and depositional behavior at this upstream reach does not suggest a strong influence of the downstream removed dam.

The upstream restored reach, OR3, experienced net erosion during most bathymetric surveys that do not coherently correspond to substrate grainsize changes. This site experienced substantial in-channel engineering activities, including heavy machinery within the channel and riverbed regrading. Observed erosion may reflect ongoing adjustment of the newly engineered channel, which may overwhelm any potential influence of the removed downstream dam.

In the downstream reach OR4, DoDs indicate patterns of concurrent deposition and erosion within a given survey instead of dominant reach-scale erosion or deposition for a given survey observed in the unrestored and restored upstream reaches. Finally, OR1 experienced some periods of net deposition and erosion underscoring the background variability of this river system that seem to correspond to seasonal differences in streamflow magnitudes and sediment supply.

Coarsening may be a result of either (1) within-reach fines being winnowed leaving coarser clasts in place or (2) new coarse material being transported into and deposited within the reach. Interestingly, the out-of-phase behavior between upstream and downstream of the removed dam reaches suggests that response to streamflow and sediment transport dynamics are not the same system-wide, but are influenced by reach scale hydraulic conditions. For example, we attribute fining in the upstream reaches during summertime flows to sediment laden streamflows during this period that are causing deposition of fines, but this does not necessarily translate to the same response in the downstream reach.

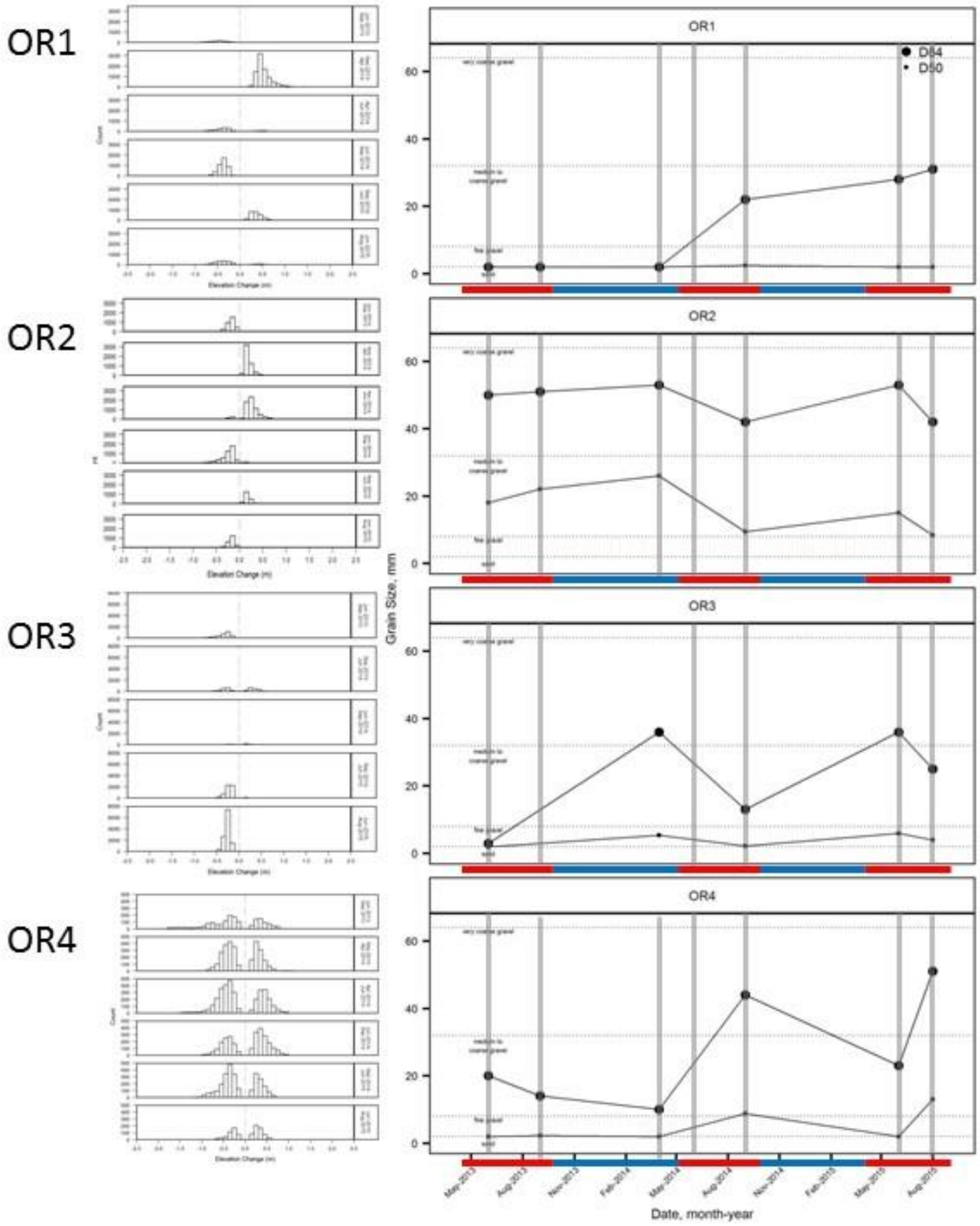

Figure 4. Comparison of reach-scale bathymetric changes and representative substrate clast sizes during the study period at four study sites (OR1-OR4) in the Olentangy River. Left panels are frequency distribution of DEM of Differencing (DEM_{Time2}-DEM_{Time1}) values for each 1-m grid cell within each study reach. Negative values indicate erosion. Positive values indicate deposition. Right panels are reach-averaged changes in D50 and D84 substrate sizes for the study period. Vertical lines indicate bathymetry surveys. Red and blue bars represent summer and winter-spring seasons.

Ecological component

Ecological sampling was conducted prior to and for three years following dam removal. This project investigated the consequences of lowhead dam removal for (1) fish assemblage structure and (2) the responses of benthic macroinvertebrate and fish community to riffle development following dam removal. For the purposes of this report, we have included data thru August 2014 for (1) and thru August 2015 for (2).

Ecological sampling was conducted prior to and after dam removal during the summer and early fall. Upstream fish assemblage (at restored reach) composition shifted significantly and was accompanied by a significant decrease in species richness and diversity. These changes represented changes in the relative abundance of taxa within different feeding guilds. Specifically, reductions in species richness and diversity at the upstream reaches were accompanied by the loss of large-bodied omnivorous species. Between year 1 and year 2 post-dam removal, diversity increased significantly at the upstream restored and downstream reaches. Species richness increased significantly at the upstream restored reach and showed an increasing trend at the upstream unrestored and downstream reach. Shifts in fish assemblages as the upstream restored and downstream reaches were accompanied by a substantial increase in insectivorous species including an increase in darter (*Etheostoma* spp.) species.

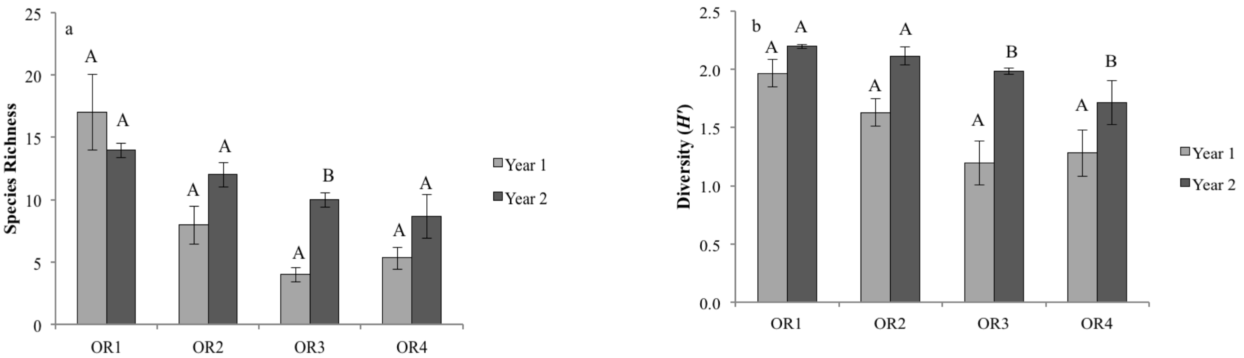

Figure 5. Fish assemblage (a) species richness and (b) diversity (*H*') in years 1 & 2 following dam removal of the Olentangy River study reaches. OR1 is the upstream of an existing dam control reach; OR2 is the upstream of the removed dam, unmanipulated experimental reach; OR3 is the upstream of the removed dam, restored experimental reach; and OR 4 is the downstream of the removed dam experimental reach. Significant differences based on *t*-tests are indicated by different letters ($p < 0.05$). Error bars represent ±1 SE from the mean. From Dorobek, Sullivan, and Kautza (2015).

For the component of the study related to riffle development following dam removal, we found that the density and diversity of macroinvertebrates and fish were significantly different over time, largely as a function of season (lowest densities in early spring, greatest in summer). Nevertheless, we also found within-season changes (e.g., macroinvertebrate density declined by 50% from summer 2014 to late spring 2015). Macroinvertebrate assemblage composition was different by time but not riffle, whereas fish assemblages were similar irrespective of time or riffle. Sediment-size distributions, water depth, and streamflow velocities varied by riffle and over time. Overall, chemical water quality (e.g., phosphate [PO_4] and dissolved oxygen [DO]) was more strongly related to macroinvertebrate communities and hydrogeomorphic parameters (e.g., streamflow velocity and substrate size) were more strongly related to fish.

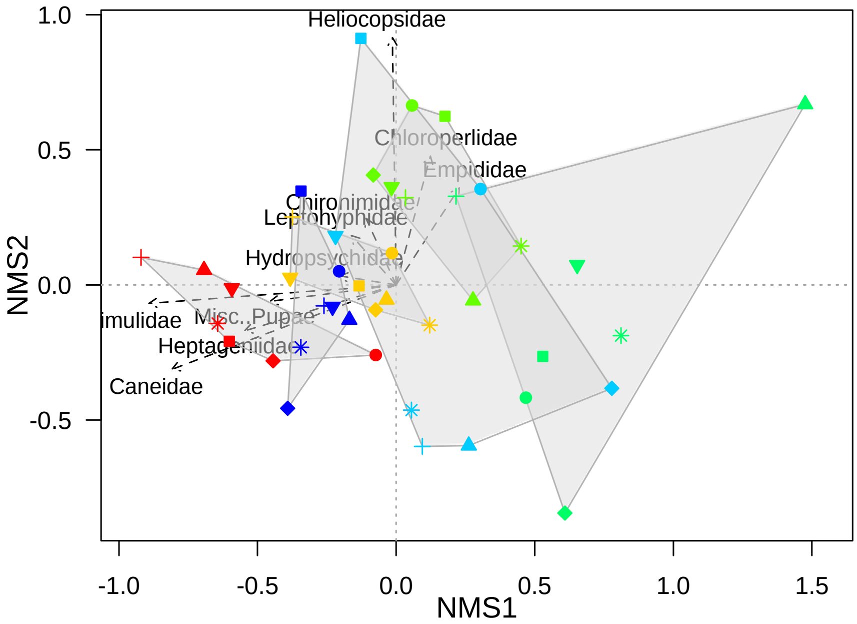

Figure 6. Non-metric Multidimensional Scaling (NMS) ordination plots of benthic macroinvertebrate assemblage compositions grouped by date (scaled by variance). The stress level was 22%, respectively. The different shapes indicate the different riffles and the different colors indicate the different sampling time periods; only the most significant families are indicated. Dates: June 2014 = red, August 2014 = yellow, November 2014 = green, March 2015 = cyan, June 2015 = blue. Riffles are shown by symbol: Riffle 1 = circle, Riffle 2 = square, Riffle 3 = diamond, Riffle 4 = triangle (up), Riffle 5 = triangle (down), Riffle 6 = asterisk, Riffle 7 = plus. From Cook and Sullivan (In Review).

Significance

This project quantifies linked geomorphic and ecological response to removal of a lowhead dam with respect to fish community assemblages, as well as how lowhead dam removal influence riffle development and both fish and macroinvertebrate communities. The geomorphic influence of dam removal on fish community assemblages builds on documented community shifts in aquatic biota following dam removal. Collectively, our results indicate that geomorphic alterations, in conjunction with water-quality changes, may be key mechanisms related to restoring biological diversity following dam removal. This study represents a higher level of system integration with intensive coupled geomorphic and ecological metrics than is common, and the results will be useful in informing future dam removal efforts.

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