Geomorphic Response to Lowhead Dam Removal in a Mid-Sized Urban River System

THESIS

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Abstract

As lowhead dams (< 7.5 m in height, run-of-river structures) are reaching the end of their functionality or structural integrity, their removal has become an increasingly popular river management and restoration practice. Geomorphic adjustment to dam removal is an emerging science; however, studies are limited that track the character of geomorphic change, particularly the short-term (intervals of only a few months) changes that occur in first few years following dam removal, which can have critical consequences on ecosystem processes occurring over these time scales.

The present study reports on the geomorphic responses of the Olentangy and Scioto Rivers (Columbus, Ohio, USA) following two lowhead dam removals within an urban landscape. This study used a paired control-treatment design to quantify the geomorphic response of river channel reaches (~ 450 m long) above and below a removed lowhead dam and compare these responses to geomorphic behavior above and below existing lowhead dams over the same time period. Reaches upstream of removed dams included those which were passively-restored and actively-restored, which consisted of in-channel engineering activities. Geomorphic change was quantified through repeat bathymetric surveys using an acoustic Doppler current profiler (ADCP) and near-surface riverbed substrate sampling at several time periods (~ 2 surveys per year) within the 2-3 years following dam removal. The objective of this study was to characterize the nature of geomorphic response in terms of sediment transport processes,
which was achieved through quantitative and qualitative comparison of erosion and deposition patterns, development and evolution of in-channel macrofeatures, such as the thalweg and pools, changes in reach-scale metrics of heterogeneity, and changes in riverbed substrate.

Results indicate an overarching trend of summer erosional and winter depositional processes throughout the river system with some coinciding coarsening and fining of riverbed substrate and significant changes in reach topographic heterogeneity. Reaches upstream of the removed lowhead dams were net erosional for the duration of the study, which was likely a result of the removal of previously impounded sediments. Even though there were observed patterns of seasonal coarsening and fining, the upstream reaches had overall coarsening of riverbed substrate (by 22 mm and 17 mm on the Olentangy and Scioto Rivers, respectively). The restored reaches also saw the establishment of pools and runs, with some changes in topographic heterogeneity over time. Downstream of the dam removal, the Olentangy River and Scioto Rivers were net erosional and net depositional, respectively; substrate initially fined at both reaches (by 10 and 5 mm, respectively) but coarsened for the overall study period. Macrofeatures experienced moderate adjustments attributed to sediment movement through the reach, with little change in topographic heterogeneity.

The results of this study contribute to the growing body of knowledge surrounding dam removals, highlighting that observed geomorphic changes reflect in part differences in the seasonal character of streamflow and sediment regimes.
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Chapter 1 – Review of Research on Impacts of Lowhead Dams on Rivers and Geomorphic Responses to Lowhead Dam Removal

1.1 Presence of Lowhead Dams on Rivers

The United States and its major river systems in the lower 48 states have seen the construction of approximately 2.5 million dams (National Research Council, 1992), with the highest concentration of dam construction occurring between 1950 and 1970 (H. John Heinz III Center, 2002). Approximately 2 million of those dams are considered lowhead dams, most of which are not accounted for in the US Army Corps of Engineers (USACE) National Inventory of Dams (NID) (Graf, 1993). Variable definitions of lowhead dams exist. For the purposes of this thesis, a lowhead dam can be defined as a constructed barrier in a river with a hydraulic height (head water to tail water) not exceeding 7.6 meters (m); this can also include run-of-river dams (AASHTO, 2005). Csiki and Rhoads (2010) define a run-of-river dam as “a structure that extends across the width of a stream or river channel, has no mechanisms inhibiting discharge of water over the dam, and is of a height that generally does not exceed elevation of the channel banks upstream.” Not all lowhead dams are registered within the NID since they are not considered to be dams of “environmental consequence,” which includes 1) those greater than 1.83 m high with more than 61,700 m$^3$ of storage, 2) those greater than 8 m high with more than 18,500 m$^3$ of storage, or 3) those of any size that pose a significant downstream threat to human
lives or property (Graf, 1999). Nationally, 49% of NID registered dams are considered lowhead dams. Of the 1,483 NID registered dams in Ohio, 611 (41%) are lowhead dams (USACE, 2013).

1.1.1 Upstream and Downstream Geomorphic Impacts of Dams

There is a considerable understanding of how an existing dam affects the geomorphology of a river. Dams interrupt connectivity between upstream and downstream portions of a river system. The channel morphology of a river is the physical template that serves as habitat for a variety of aquatic organisms (Ligon et al., 1995). Upstream consequences of a dam include increased water depth and surface area (Pizzuto, 2002) and flooding of riparian habitats from the resulting reservoir upstream of the dam (Shafroth et al., 2002). Mean water velocities decrease in the downstream direction through the reservoir as the dam is approached (Burroughs et al., 2009). This disruption in natural flow (Doyle et al., 2005) characterized by slower velocities causes sediment deposition within the reservoir upstream of the dam (Stanley and Doyle, 2003) that extends to reaches upstream of the reservoir that are affected by backwater (Kondolf, 1997).

Sediment entrapment within a reservoir disrupts sediment transport processes within the river and reduces sediment supply, both suspended and bedload, to downstream reaches (Rumschlag and Peck, 2007; Stanley and Doyle, 2003). The response to the altered flow regimes and the diminished sediment supply is governed by the overarching geologic controls of the watershed (Grant et al., 2003), but can be variable (Collier et al., 1996; Williams and Wolman, 1984) across different watersheds.
Water released from the dam has been referred to as “hungry water” as a consequence of excess energy that is no longer expended on carrying sediment, which is now trapped behind the dam (Kondolf, 1997). This energy is then available for geomorphic processes on the downstream channel bed and banks, which can include streambed incision with subsequent development of a coarse-grained, armored channel bed, channel narrowing, or bank erosion and widening, depending on the sediment type (Kondolf, 1997; Petts, 1984; Pizzuto, 2002). The channel narrowing can potentially expand the floodplain area and increase the area available for riparian vegetation to inhabit. Channel narrowing occurs as a consequence of reduced flood magnitudes and subsequent riparian vegetation encroachment (Ligon et al., 1995), which sometimes leads to expansion of the floodplain area downstream of dams (Shafroth et al., 2002).

Alternatively, the downstream channel adjustment in response to a dam could be bank erosion resulting in channel widening (Csiki and Rhoads, 2014). Collectively, channels may develop a simplified morphology downstream of dams as transient in-channel sediment bars are removed and higher elevation surfaces and floodplains are stabilized by reduced and homogenized discharge magnitudes (Ligon et al., 1995). The particular downstream channel response will be a function of both 1) bank substrate and riparian vegetation material and 2) downstream flow regime (Rumschlag and Peck, 2007).

1.2 Lowhead Dam Removal

By the year 2020, 80% of the dams in the U.S. that are 1.8 m or higher will have reached at least 50 years of age, and will be considered at the end of their projected
design life (Evans et al., 2000). Problems associated with these aging dams include 1) sediment-filled reservoirs, which reduce water storage and flood control capacity, 2) impaired structural integrity, which causes issues of liability and maintenance, and 3) sustained geomorphic and ecological impacts of dams (Evans et al., 2000; Heinz Center, 2002).

As stated previously, a wide breadth of literature exists concerning how the presence of a dam affects geomorphic processes, which shapes the physical channel form that serves as habitat for aquatic organisms, both upstream and downstream of the dam (Fencl et al., 2015; Graf, 1999; Poff and Hart, 2002; Poff et al., 1997). As dams reach the end of their functionality, the practice of their removal rather than repairing or maintaining has become a more common management and restoration practice (Evans et al., 2000; Poff and Hart, 2002). As a consequence, there is increasing interest in understanding physical channel adjustment once a dam is removed (Stanley and Doyle, 2003) since geomorphic response to dam removal is a growing and evolving research field (Table 1.2, Table 1.2). Early geomorphic research on dam removal assumed that the channel would return to pre-dam conditions (Stoker and Harbor, 1991). However recent research suggests that the particular character of channel response to dam removal can be complex and may vary across short (< 2 years) and longer term (2-10 years) timescales (Stanley and Doyle, 2003). Complex and spatially variable geomorphic adjustment is a consequence of the combined dam and channel conditions that includes variations in dam height, the character of channel sediment both upstream and downstream of the dam, channel gradient through the dam, corresponding land use, and geologic condition (Grant et al., 2003; Pizzuto, 2002). Given such varying conditions, research in channel response
to dam removal is continuing to evolve as dams are more dams are being removed. In addition, many dam removal projects will utilize active channel restoration, such as regrading and revegetating (Pizzuto, 2002), to accelerate the channel recovery process, especially in publically visible reaches of a river.

1.2.1 Upstream and Reservoir Geomorphic Channel Responses

With the removal of a lowhead dam, the reservoir transitions from a sediment sink to a sediment source and fine sediment (e.g. sand, silt, and clay that have < 2 mm grain size diameter; Wolman, 1954) leaves the reservoir as it is dewatered (Doyle et al., 2003). The Channel Evolution Model (CEM) is a conceptual model described Simon and Hupp (1986) modified by Doyle et al. (2002) that describes the six stages of the geomorphic changes within the reservoir upstream of a dam removal (Figure 1.1). The stages include 1) pre-removal, 2) lowered water surface following dam removal, 3) degradation into the reservoir sediment, 4) degradation and widening, 5) aggradation and widening, and finally 6) quasi-equilibrium. This last stage is a condition between river discharge, flow regime, sediment load, and channel slope that is constantly trying to be met through the adjustment of interdependent hydraulic variables (e.g. channel width and depth, flow velocity, bed and bank roughness, and bed slope; Kusky and Cullen, 2010). The complete sequence of typical conceptual channel models likely requires at least a decade and is highly dependent on the character of reservoir sediments including grain size and amount stored in the reservoir (Pizzuto, 2002). Many dam removals are compared to the CEM and amendments are suggested based on case study observations and conclusions.
Erosion of reservoir sediments is the most common and immediate response to dam removal, which is characterized by vertical incision followed by lateral erosion and widening of the newly formed channel (Table 1.1). At first, sediment export is driven by the upstream migration rate of a knickpoint or head cut (Figure 1.1) through the reservoir sediment (Burroughs et al., 2009; Doyle et al., 2003; Wildman and MacBroom, 2005). A knickpoint is an oversteepened break in the longitudinal profile of a stream characterized by erosion, therefore causing the point to migrate upstream along the stream profile (Schumm et al., 1984). The headcut that developed following the removal of the 3.3 m Rockdale dam in Wisconsin (Table 1.1) incised into 2 m of fine reservoir sediment and caused mass wasting of the banks and some channel widening near the dam; sediment upstream of the headcut remain mostly unchanged (Doyle et al., 2003). The wetted-width of a former reservoir generally decreases over time as the channel narrows and the thalweg deepens (Burroughs et al., 2009; Doyle et al., 2003). Dam removal causes
subsequent sediment exposure, erosion, and redistribution that are associated with the reinstatement of streamflow through the former reservoir.

In the most general sense, dam removal converts a reservoir into a flowing river with bordering riparian habitat and floodplain (Stanley and Doyle, 2003). After the initial degradation, the channel undergoes a period of aggradation along the margins due to the newly available, erodible sediment in the more upstream portions of the reservoir (Doyle et al., 2003). For example, after the erosion and transport of the finer sediment, newly exposed coarser sediment (e.g. gravel, cobble, and boulder with grainsize diameters > 2 mm; Wolman, 1954) became available for erosion during higher flow events on the Baraboo River in Wisconsin following the removal of the 2-m LaValle dam (Doyle et al., 2003). After dam removal, stable, consolidated sediment within a reservoir might not erode as easily as finer sediments and may develop into the floodplain if not located within the newly developing channel (Doyle et al., 2002). The new floodplain may be further stabilized by rapid establishment of vegetation (Shafroth et al., 2002). Reservoirs with less consolidated sediment can cause a larger portion of sediment to be rapidly transported downstream once the dam is removed (Doyle et al., 2002).

After dam removal, the amount, rate, and pattern of sediment erosion from the former reservoir can be quite variable, depending on the channel slope, newly established flow velocity, and the amount and type of sediment (Hart et al., 2002). Following the gradual removal of the 4-m Stronach dam in Michigan, 12% of the estimated stored sediment had eroded after 10 years, with 14% of the eroded sediment remaining within 1 km downstream of the former dam (Burroughs et al., 2009). Similarly, the stepwise
removal of the 2.4-m Brewster dam in Illinois resulted in approximately 13% of the reservoir sediment eroding during and within 3 years of the dam removal (Straub, 2007).

Larger dams that were rapidly removed have experienced similar percentage of sediment export in a much smaller time frame. The 38-m Condit dam (Washington) removal eroded approximately 20% of the reservoir sediment in 24 hours and approximately 55% within the 15 week study (Wilcox et al., 2014). The 15-m Marmot dam (Oregon) removal exported 15% of its reservoir sediment within 60 hours and 56% within 15 months; there was minimal additional sediment erosion reported during the remainder of the second year following the dam removal (Major et al., 2012). Finally, in Washington, the 32-m Elwha and 64-m Glines Canyon dams’ 2 year staged removals eroded 23% and 37%, respectively, of their reservoir sediment in that time period (Randle et al., 2015), with approximately 10% of the eroded sediment of both reservoirs remaining within the 18 km of mainstem channel and 25 km of floodplain channels downstream; most sediment had been transported to the mouth of the Elwha River (East et al., 2015).

Based on the findings of 12 dam removal case studies, Sawaske and Freyberg (2012) found that reservoirs filled with predominantly fine and consolidated or cohesive sediment showed a significant trend of retaining over 85% of their sediment volume, whereas unconsolidated or non-cohesive sand or gravel-filled reservoirs do not show a common trend. They concluded that the most influential factors for determining the rate and volume of reservoir sediment erosion are median grain size, level of cohesion, spatial
variability of deposit, and removal timeline. Additional responses upstream of dam removals are summarized in Table 1.1.

1.2.2 Downstream Geomorphic Channel Responses

The release of fine sediment from a dam can impact the downstream reach by filling pools and burying coarse-grained riffles, resulting in homogenizing the physical habitat and sediment type (Pizzuto, 2002). For months after the removal, the downstream reaches can also have elevated turbidity from the release of the fine sediment (Perrin et al., 2000). The character of geomorphic response to dam removal and delivery of coarse reservoir sediments is different relative to fine reservoir sediments (Table 1.2). The responses to the dam removal in a coarse sediment system will initially be most noticeable in the reach directly downstream of the former dam (Kibler et al., 2011; Stewart, 2006). When gravel-filled dams are breached, there can be a delay in sediment transport until there are flow events that can move the coarser sediment. This makes timing of dam removal important since normal base flow is not enough to move the stored, coarse sediment (Kibler et al., 2011). The downstream channel adjustments will take place until all of the erodible gravel within the reservoir is (Walter and Tullos, 2010), then further channel adjustments can occur through the transportation of sediment as bedload through dispersion, translation, or a combination of both processes (Pizzuto, 2002; Rumschlag and Peck, 2007). Dispersion is the diffusion of the initial sediment pulse downstream from the deposit (Lisle et al., 2001). Alternatively, translation is the process by which the mass of bed material travels downstream without losing its size (Pizzuto, 2002).
Aquatic habitats directly downstream of a former dam retaining coarse sediment can become more heterogeneous with diminishing noticeable effects as distance downstream increases (Kibler et al., 2011). Removal of the coarse sediment filled 3.2-m Dinner Creek and 3.4-m Maple Gulch dams in Oregon resulted in greatest sediment deposition near the former dam and decreasing exponentially with increasing downstream distance (Stewart, 2006). One year following the removal of the Maple Gulch dam, 74% of the eroded sediment remained within 200 m below the former dam (Stewart, 2006). Newly deposited sediment can cause the redirection of the channel thalweg, which was observed within the year following the removal of the 2-m LaValle dam in Wisconsin (Doyle et al., 2003). After the short-term development of deposits downstream of a dam removal, continued channel evolution will occur as the deposits are episodically mobilized during high flow events (Major et al., 2012).

The downstream geomorphic response to dam removal is driven by the character of delivery of reservoir sediments and the rate of channel formation within the reservoir (Doyle et al., 2003). Downstream geomorphic response from dam removal with reservoir sediments that are generally considered to be of fine diameter (e.g., primarily small gravel, sand, and silt) has been documented to be different than geomorphic response when reservoir sediments are coarse (gravel and cobble). For example, prior to removal, the 2.1-m Brownsville dam (Oregon) had accumulated 14,000 m$^3$ of coarse sediment ($d_{50} = 59$ mm) within its reservoir, while the downstream reach was characterized by exposed bedrock and hardpan with few sediment bars (Walter and Tullos, 2010). The removal caused a coarsening of downstream substrate as the channel shifted from hardpan to gravel and cobble deposits. The release of gravel increased habitat heterogeneity through
the formation of new riffles and pools close to the former dam, while little geomorphic change was observed further downstream (Kibler et al., 2011). On the other hand, the 2-m LaValle dam in Wisconsin had accumulated a 1.4-1.7 m layer of fine sediment (46% sand, 41% silt, 13% clay) within its reservoir. Following dam removal, the downstream reach experienced an initial aggradation of fine sediment along the channel margins, but between 1 and 10 months of dam removal, the majority of geomorphic changes occurred as sand was eroded from the upstream reach and was deposited immediately downstream of the former dam. This deposit was temporary; pre-removal depth and cross-sectional area returned after 3 months, and the sand accumulation was observed further downstream as a point bar formed and redirected the channel thalweg. The export of fine sediments from a dam caused temporary aggradation and caused limited changes in channel morphology (Doyle et al., 2003).

It is important to note however, that if there is little sediment store behind the dam or sediment can be readily transported over the dam, removal will likely have little effect on the downstream channel in comparison to the current natural variability (Csiki and Rhoads, 2014; Walter and Tullos, 2010). Additional responses downstream of dam removals are summarized in Table 1.2.
<table>
<thead>
<tr>
<th>Dam, height (m)</th>
<th>Years of monitoring after removal</th>
<th>Upstream/Reservoir response</th>
<th>Sediment characteristics and responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>River System Location/Region; Reference(s)</td>
<td></td>
<td>Incision</td>
<td>Width adjustment</td>
</tr>
<tr>
<td>Coho Dam, 1.5</td>
<td>removed 2002; 1 year</td>
<td></td>
<td></td>
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<tr>
<td>Huron River Ohio (Evans et al., 2007)</td>
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<tr>
<td>LaValle Dam, 2</td>
<td>removed 2000; 1 year</td>
<td>vertical incision into impound sediment</td>
<td>some rotational slumping of banks near dam</td>
</tr>
<tr>
<td>Baraboo River Wisconsin (Doyle et al., 2003)</td>
<td></td>
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<tr>
<td>Manatawny Creek Dam, 2</td>
<td>removed 2000; 1 year</td>
<td>0.5 m erosion of fine sediment</td>
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<tr>
<td>Manatawny Creek Pennsylvania (Bushaw-Newton et al., 2003)</td>
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<tr>
<td>St. Johns Dam, 2.2</td>
<td>removed 2003; 10 months</td>
<td>reservoir experienced decreased bedslope; 0.5m degradation</td>
<td>no significant change in channel widths</td>
</tr>
<tr>
<td>Sandusky River Ohio (Cheng and Granata, 2007; Granata et al., 2008)</td>
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</table>

Table 1.1 Listing of dam removal studies, locations, dam heights, references, years of monitoring, upstream geomorphic response, and sediment characteristics and responses.
<table>
<thead>
<tr>
<th>Dam, height (m)</th>
<th>River System</th>
<th>Location/Region; Reference(s)</th>
<th>Years of monitoring after removal</th>
<th>Upstream/Reservoir response</th>
<th>Sediment characteristics and responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brewster Dam, 2.4</td>
<td>Brewster Creek</td>
<td>Illinois (Straub, 2007)</td>
<td>stepwise removal 2003-2004; 3 years</td>
<td>channel incision until original streambed material reached, then widening; knickpoint formed after first notch and developed with more notches and high flow events</td>
<td>prior to removal, reservoir sediment was on average 1.1 m thick, consisted of 67-99% silts and clays and downstream sediment was characterized as sand, gravel, and cobble; approximately 13% of reservoir sediment eroded during/after removal</td>
</tr>
<tr>
<td>Union City Dam, 2.4</td>
<td>Naugatuck River</td>
<td>Connecticut (Wildman and MacBroom, 2005)</td>
<td>removed 1999; 5 years</td>
<td>rapid headcut into impound sediment; eventual formation of unusually deep and narrow channel further upstream</td>
<td>widening due to riffle formation over buried pipe and scour pool formed downstream of pipe but filled over time, which allowed headcut to continue upstream at deeper elevation</td>
</tr>
<tr>
<td>Kimages Creek Dam, 3</td>
<td>Kimages Creek</td>
<td>Virginia (Cannatelli and Curran, 2012)</td>
<td>partial failure 2006; 2 years</td>
<td>narrowing and deepening of channel; periods of degradation and aggradation</td>
<td>most adjustment occurred in channel/reach more recently drained; CEM needs to factor in seasonal hydrology at time of removal and ability of vegetation to establish on and stabilize channel banks</td>
</tr>
<tr>
<td>Dam, height (m)</td>
<td>River System Location/Region; Reference(s)</td>
<td>Years of monitoring after removal</td>
<td>Upstream/Reservoir response</td>
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<tr>
<td>Dinner Dam, 3.2 Dinner Creek Oregon (Stewart, 2006)</td>
<td>removed 2003; less than 1 year</td>
<td>event-driven knickpoint progression</td>
<td>coarse sediment system; 36% of eroded reservoir sediment remained within 150 m of former dam</td>
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<tr>
<td>Rockdale Dam, 3.3 Koshkonong River Wisconsin (Doyle et al., 2003)</td>
<td>removed 2000; 1 year</td>
<td>channel developed via headcut migration; sediment upstream of headcut mostly unchanged, but downstream had substantial incision into reservoir sediment (2 m fine then coarse)</td>
<td>incision near dam caused mass-wasting of banks and some channel widening; further upstream erosion exposed sand, some of which was later deposited within former reservoir</td>
<td>mixed sediment</td>
<td></td>
</tr>
<tr>
<td>Anaconda Dam, 3.4 Naugatuck River Connecticut (Wildman and MacBroom, 2005)</td>
<td>removed 1999; 5 years</td>
<td>headcutting and incision into impound sediment until underlying armored channel was reached</td>
<td>formation of a major and minor channel, but horizontal migration caused widening of major channel and loss of minor channel; minor aggradation at banks from upstream bed material (not from bank failures)</td>
<td>coarse sediment; 1/3 of reservoir sediment eroded; partial breach prior to removal</td>
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<tr>
<td>Maple Dam, 3.4 Maple Gulch Oregon (Stewart, 2006)</td>
<td>removed 2002; 1 year</td>
<td>event-driven knickpoint progression</td>
<td>coarse sediment system; 74% of eroded reservoir sediment remained within 200 m of former dam</td>
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<td>Dam, height (m)</td>
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<tr>
<td>Munroe Falls Dam, 3.7</td>
<td>Middle Cuyahoga River Ohio</td>
<td>removed 2005; 2 years</td>
<td>initial downcutting until underlying bedrock was reached</td>
<td>widening occurred via slumping due to cohesive sediment</td>
<td></td>
</tr>
<tr>
<td>Merrimack Dam, 3.9</td>
<td>Souhegan River New Hampshire</td>
<td>removed 2008; 2 years</td>
<td>process-driven for 3 months characterized by rapid incision and exporting of sand (1013 metric tons/day, removed 50% by volume), followed by channel widening; once incision reached base level, the rate of sediment removal decreased (30.7 tons/day) and therefore channel adjustments were driven by events of high flow (event-driven)</td>
<td>for sand filled reservoirs, initial channel development and erosion occurs within a matter of weeks to months, with additional erosion occurring at a slower rate and driven by vegetation establishment and high flow events</td>
<td>sand-filled dam; 79% of reservoir sediment had been eroded (owed to the dam removal and two high magnitude floods)</td>
</tr>
<tr>
<td>Stronach Dam, 4</td>
<td>Pine River Michigan</td>
<td>staged removal 1996-2003; 10 years (1996-2006)</td>
<td>progressive headcutting; incision into impound sediment caused narrower and deeper channel with coarser substrate</td>
<td>higher velocity development</td>
<td>only 12% of estimated reservoir sediment eroded (14% of which remained within 1 km downstream of former dam)</td>
</tr>
</tbody>
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<thead>
<tr>
<th>Dam, height (m) River System Location/Region; Reference(s)</th>
<th>Years of monitoring after removal</th>
<th>Upstream/Reservoir response</th>
<th>Sediment characteristics and responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVEX Dam, 7.4 Chagrin River Ohio (Evans, 2007; Evans et al., 2000)</td>
<td>failure 1994; 12 years</td>
<td>incision into reservoir mobilized sediment as it re-established hydraulic gradient</td>
<td>after 12 years, confirms Doyle et al (2003) CEM (A-F), but proposes a few amendments: 1) stage A2 indicates presence of some scour/erosion within the reservoir; 2) B’ consists of an early-breach, dendritic drainage network formed by incision of cohesive reservoir sediment, later gave way to re-establishment of main channel; 3) E1 shows lateral channel migration caused by incision, undercutting, and channel bank failures by slumping; fine sediment; 9-13% of reservoir sediment eroded in 2 months (61-86% remained stored in downstream dam reservoir); surveyed at 2 months and 12 years</td>
</tr>
<tr>
<td>Marmot Dam, 15 Sandy River Oregon (Major et al., 2012)</td>
<td>removed 2007; 2 years</td>
<td>rapid knickpoint migration caused vertical incision; initial formation of steep gradient which diminished over time; incision caused channel widening due bank collapse of unconsolidated sediment</td>
<td>rate of knickpoint migration slowing over time; little erosion within second year after removal; sand and gravel sediment; 15% of reservoir sediment eroded in 60 hours, 56% in 15 months</td>
</tr>
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<tr>
<th>Dam, height (m)</th>
<th>Location/Region; Reference(s)</th>
<th>Years of monitoring after removal</th>
<th>Upstream/Reservoir response</th>
<th>Sediment characteristics and responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elwha Dam, 32</td>
<td>Elwha River Washington (East et al., 2015; Randle et al., 2015)</td>
<td>staged removal 2011-2013; 2 years (2011-2013)</td>
<td>degradation/incision slowed when pre-dam surface reached;</td>
<td>generally followed channel evolution steps and were able to observe these steps at different locations and times within reservoir since reservoir was slowly drained; quasi-equilibrium somewhat reached but likely to shift more because of lack of flood and future influx of sediment from Lake Mills after rest of Glines Canyon dam removal</td>
</tr>
<tr>
<td>Barlin Dam, 38</td>
<td>Dahan River Taiwan (Tullos and Wang, 2014)</td>
<td>failure 2007; 5 years</td>
<td>deep thalweg incision (18 m in 3 months); migration of kickpoint/headcut steepened gradient</td>
<td>rapid erosion very close to dam with little change after; incision of channel further upstream was delayed a year</td>
</tr>
<tr>
<td>Condit Dam, 38</td>
<td>White Salmon River Washington (Wilcox et al., 2014)</td>
<td>removed 2011; 15 weeks</td>
<td>massive erosion of fine sediment; erosion via knickpoint migration, channel incision, and small mass failures</td>
<td>rates of adjustment slowing over time</td>
</tr>
<tr>
<td>Dam, height (m) River System Location/Region; Reference(s)</td>
<td>Years of monitoring after removal</td>
<td>Upstream/Reservoir response</td>
<td>Sediment characteristics and responses</td>
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<tr>
<td>Glines Canyon Dam, 64 Elwha River Washington (East et al., 2015; Randle et al., 2015)</td>
<td>3/4 removed over 2 years (2011-2013)</td>
<td>incision: knickpoint migration upstream and length of sediment erosion channel increased, but slowed and stalled during low flows and when met cobble/boulder; higher flows necessary to continue migration of knickpoint; degradation/incision slowed when pre-dam surface reached;</td>
<td>width adjustment: degradation and narrowing: multiple channels gave way to dominant degrading channel; degradation and widening: widening more rapid when flow was greater but still influenced by sediment (coarse/noncohesive or fine layers); further aggradation from upstream reaches; generally followed channel evolution steps and were able to observe channel evolution steps at different locations and times within reservoir; quasi-equilibrium not yet reached because more of dam has yet to be removed</td>
<td>37% of reservoir sediment eroded within 2 years</td>
</tr>
<tr>
<td>Dam, height (m)</td>
<td>River System</td>
<td>Location/Region; Reference(s)</td>
<td>Years of monitoring after removal</td>
<td>Downstream response</td>
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</tr>
<tr>
<td>LaValle Dam, 2</td>
<td>Baraboo River</td>
<td>Wisconsin (Doyle et al., 2003)</td>
<td>removed 2000; 1 year</td>
<td>initial aggradation of fine sediment and later temporary sand aggradation; sand deposition further downstream influenced thalweg direction</td>
</tr>
<tr>
<td>Manatawny Creek</td>
<td>Manatawny Creek</td>
<td>Pennsylvania (Bushaw-Newton et al., 2003)</td>
<td>removed 2000; 1 year</td>
<td>fine sediment aggradation</td>
</tr>
<tr>
<td>Brownsville Dam, 2.1</td>
<td>Calapooia River</td>
<td>Oregon (Kibler et al., 2011; Walter and Tullos, 2010)</td>
<td>removed 2007; 2 years</td>
<td>coarsening of substrate (shift from hardpan to gravel/cobble); gravel released from dam increased habitat heterogeneity close to dam with little geomorphic change further downstream</td>
</tr>
<tr>
<td>St. Johns Dam, 2.2</td>
<td>Sandusky River</td>
<td>Ohio (Cheng and Granata, 2007; Granata et al., 2008)</td>
<td>removed 2003; 10 months</td>
<td>some aggradation of finer sediment</td>
</tr>
</tbody>
</table>

Table 1.2 Listing of dam removal studies, dam heights, locations, references years of monitoring, downstream geomorphic response, and sediment characteristics and responses.
<table>
<thead>
<tr>
<th>Dam, height (m)</th>
<th>River System Location/Region; Reference(s)</th>
<th>Years of monitoring after removal</th>
<th>Downstream response</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Union City Dam, 2.4</strong> Naugatuck River Connecticut (Wildman and MacBroom, 2005)</td>
<td>removed 1999; 5 years</td>
<td>no accumulation of sediment immediately downstream</td>
<td>channel became deeper and narrower</td>
</tr>
<tr>
<td><strong>Dinner Dam, 3.2</strong> Dinner Creek Oregon (Stewart, 2006)</td>
<td>removed 2003; less than 1 year</td>
<td>sediment deposition greatest near former dam and decreased exponentially with increasing downstream distance</td>
<td>coarse sediment system; 36% of eroded reservoir sediment remained within 150 m of former dam</td>
</tr>
<tr>
<td><strong>Rockdale Dam, 3.3</strong> Koshkonong River Wisconsin (Doyle et al., 2003)</td>
<td>removed 2000; 1 year</td>
<td>little in-channel deposition of fine sediment</td>
<td>mixed sediment</td>
</tr>
<tr>
<td><strong>Anaconda Dam, 3.4</strong> Naugatuck River Connecticut (Wildman and MacBroom, 2005)</td>
<td>removed 1999; 5 years</td>
<td>sediment bars undergoing translation and dispersion</td>
<td>coarse sediment; 1/3 of reservoir sediment eroded; partial breach prior to removal</td>
</tr>
<tr>
<td><strong>Maple Dam, 3.4</strong> Maple Gulch Oregon (Stewart, 2006)</td>
<td>removed 2002; 1 year</td>
<td>sediment deposition greatest near former dam and decreased exponentially with increasing downstream distance</td>
<td>coarse sediment system; 74% of eroded reservoir sediment remained within 200 m of former dam</td>
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<tr>
<th>Dam, height (m)</th>
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<tbody>
<tr>
<td>Munroe Falls Dam, 3.7</td>
<td>Middle Cuyahoga River Ohio</td>
<td>(Rumschlag and Peck, 2007)</td>
<td>removed 2005; 2 years</td>
<td>aggradation of sediment; sand transported as bedload</td>
<td>sand-filled dam; 79% of reservoir sediment had been eroded (owed to the dam removal and two high magnitude floods)</td>
</tr>
<tr>
<td>Merrimack Dam, 3.9</td>
<td>Souhegan River New Hampshire</td>
<td>(Pearson et al., 2011)</td>
<td>removed 2008; 2 years</td>
<td>first 24 days saw initial aggradation of bed (mean 2.1 m) and narrowing (mean 17 m); next 58 days saw incision (mean 0.35 m) and widening (mean 11 m); incision (mean 1.2m) and widening (mean 9.3m) continued over the next year which lowered the thalweg back to pre-dam removal levels in some locations</td>
<td>only 12% of estimated reservoir sediment eroded (14% of which remained within 1 km downstream of former dam)</td>
</tr>
<tr>
<td>Stronach Dam, 4</td>
<td>Pine River Michigan</td>
<td>(Burroughs et al., 2009)</td>
<td>staged removal 1996-2003; 10 years (1996-2006)</td>
<td>aggradation caused wider and shallower channel; little change to substrate size</td>
<td>increased velocity as a result of increased slope</td>
</tr>
<tr>
<td>IVEX Dam, 7.4</td>
<td>Chagrin River Ohio</td>
<td>(Evans, 2007; Evans et al., 2000)</td>
<td>failure 1994; 12 years</td>
<td>deposition of fine sediment in downstream reservoir (behind second dam) and in floodplain between the two reservoirs</td>
<td></td>
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<thead>
<tr>
<th>Dam, height (m)</th>
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<tbody>
<tr>
<td>Marmot Dam, 15 Sandy River Oregon (Major et al., 2012)</td>
<td>removed 2007; 2 years</td>
<td>sediment deposition controlled by gradient discontinuities and valley morphology</td>
<td>continued channel evolution as deposits are episodically mobilized</td>
<td>sand and gravel sediment; 15% of reservoir sediment eroded in 60 hours, 56% in 15 months</td>
</tr>
<tr>
<td>Elwha Dam, 32 Elwha River Washington (East et al., 2015; Randle et al., 2015)</td>
<td>staged removal 2011-2013; 2 years (2011-2013)</td>
<td>little sediment accumulated in thalweg during first year; after two years, of the sediment released from both reservoirs, approximately 10% remained in mainstream and floodplain channels (gravel, sand), most transported further downstream to river mouth; sediment supply and accompanying bedload were large while peak flow hydrology unusually low</td>
<td>greater response in second year from sediment released from further upstream Lake Mills (Glines Canyon dam removal); bed aggradation (~1 m) caused formation of braided channels and decreased slope in lower reach of river; within 1 year of major sediment aggradation, localized incision occurred;</td>
<td>23% of reservoir sediment eroded within 2 years</td>
</tr>
<tr>
<td>Barlin Dam, 38 Dahan River Taiwan (Tullos and Wang, 2014)</td>
<td>failure 2007; 5 years</td>
<td>rapid aggradation, with most occurring in wide channel 1380 m downstream followed by immediately downstream of dam</td>
<td>some channel transitioning from single to multiple channel; distance from dam determined magnitude and rate of channel change</td>
<td>23% of reservoir sediment eroded within 2 years</td>
</tr>
<tr>
<td>Condit Dam, 38 White Salmon River Washington (Wilcox et al., 2014)</td>
<td>removed 2011; 15 weeks</td>
<td>sediment transported via suspension then as bedload; aggradation of sand followed by incision</td>
<td>reservoir had fine sediment (60% sand, 35% silt, 5% gravel); rapid removal; 20% reservoir sediment eroded in 24 hours, 55% within 15 weeks</td>
<td>23% of reservoir sediment eroded within 2 years</td>
</tr>
</tbody>
</table>

Continued
<table>
<thead>
<tr>
<th>Dam, height (m) River System Location/Region; Reference(s)</th>
<th>Years of monitoring after removal</th>
<th>Downstream response</th>
<th>Sediment characteristics and responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glines Canyon Dam, 64 Elwha River Washington (East et al., 2015; Randle et al., 2015)</td>
<td>3/4 removed over 2 years (2011-2013)</td>
<td>same as for Elwha Dam removal</td>
<td>37% of reservoir sediment eroded within 2 years</td>
</tr>
</tbody>
</table>
1.3 Literature Cited


Csiki, S.J.C., Rhoads, B.L., 2014. Influence of four run-of-river dams on channel


Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. Incised channels: morphology,
dynamics and control. Water resources publications, Littleton, Colo.


Chapter 2 – Geomorphic Response to Lowhead Dam Removal in a Mid-Sized Urban River System

Abstract

The removal of lowhead dams (< 7.5 m in height, run-of-river structures) has become an increasingly popular river management and restoration practice. As a consequence, there is growing interest in understanding physical channel adjustment once a dam is removed as studies are limited that track the particular character of geomorphic change, particularly the potential changes that occur in the first few years following dam removal, which might be expected to have critical consequences on ecosystem processes occurring over these time scales. This study reports on the geomorphic responses of the Olentangy and Scioto Rivers (Columbus, Ohio, USA) following two lowhead dam removals. This study used a paired control-treatment design to quantify the geomorphic response of river channel reaches above and below a removed lowhead dam, in comparison with reaches adjacent to existing lowhead dams. Field work included collection of repeat bathymetric surveys and near-surface riverbed substrate at several time periods within 2-3 years following dam removal, allowing for quantitative and qualitative comparison of erosion and deposition patterns, development and evolution of in-channel macrofeatures, and reach-scale metrics of heterogeneity. Results indicated an overarching trend of summer erosional and winter depositional processes throughout the river system with some
coinciding seasonal coarsening and fining of riverbed substrate and significant overall changes in reach topographic heterogeneity. Reaches upstream of the removed lowhead dams were net erosional for the duration of the study, which was likely a result of the removal of previously impounded sediments. Even though there were observed patterns of seasonal coarsening and fining, the upstream reaches had overall coarsening of riverbed substrate. The restored reaches also saw the establishment of pools and runs, with some significant changes in topographic heterogeneity. Downstream of the dam removal, the Olentangy and Scioto Rivers were net erosional and net depositional, respectively. Substrate initially fined at both reaches but coarsened for the overall study period. Macrofeatures experienced moderate adjustments attributed to sediment movement through the reach, with little change in topographic heterogeneity. These results contribute to the growing body of knowledge surrounding dam removals, highlighting that observed geomorphic changes reflect in part differences in the seasonal character of streamflow and sediment regimes.
2.1 Introduction

Dams affect over half of the large river systems in the world (Nilsson et al., 2005) and are ubiquitous features on US rivers (Graf, 1999; Stanley and Doyle, 2002). Approximately 2 million small dams (< 7.6 meters (m)) exist in the United States (Graf, 1993), many of which are considered run-of-river structures whereby water flows freely over the crest of the structure (Csiki and Rhoads, 2010). Lowhead dams often were built to provide water intakes for mills, industrial plants, and municipal drinking water (Csiki and Rhoads, 2010; James, 2005; Lorang and Aggett, 2005; Maloney et al., 2008), but are reaching the end of their functionality thus posing a considerable risk factor to public safety (Csiki and Rhoads, 2010; Doyle et al., 2003b). In addition, several studies have documented the varied geomorphic effects of dams, (reviewed in Fencl et al., 2015), as well as the associated impacts on aquatic ecosystem processes (AASHTO, 2005; Evans et al., 2007; Ligon et al., 1995; Santucci et al., 2005). The geomorphic impacts of run-of-river dams range from minimal upstream sediment accumulation as a result of trap inefficiency to significant sediment accumulation and pool infilling upstream (Csiki and Rhoads, 2010; Fencl et al., 2015; Pearson and Pizzuto, 2015; Stanley and Doyle, 2003). Consequently, dam removal has become a common restoration practice as a cost effective alternative to repairing with additional ecological benefits (Evans et al., 2000; Granata et al., 2008; Hart et al., 2002; Poff and Hart, 2002; Pohl, 2002).

Geomorphic adjustment following dam removal is an emerging science given the increase of dam removal projects (O’Connor et al., 2015; Poff and Hart, 2002; Roberts et al., 2007; Stanley and Doyle, 2003). When a dam is removed, upstream and downstream
changes to the river morphology occur and can take the form of complex, spatially variable adjustments as a consequence of site-specific conditions. In particular, the physical character of the dam, including dam height and removal method, and how much sediment is stored behind the dam can determine the potential amount of sediment that will move through the system (Csiki and Rhoads, 2010; Grant et al., 2003; Grant and Lewis, 2015; Pizzuto, 2002). The reach-scale conditions, including channel morphology, gradient, and channel bed substrate, and catchment scale characteristics of geology, hydroclimate, and land use, which influence the overarching streamflow and sediment regimes, will also determine the geomorphic response to dam removal (Cheng and Granata, 2007; Csiki and Rhoads, 2010; Grant et al., 2003).

Erosion of reservoir sediments is the most common and immediate response to dam removal (Doyle et al., 2003a; Grant and Lewis, 2015; O’Connor et al., 2015), which is characterized by vertical incision into reservoir sediments followed by lateral erosion and widening of the newly formed channel (Doyle et al., 2002; Rumschlag and Peck, 2007; Straub, 2007). Upstream knickpoint migration will slow through time, and will be driven by timing and magnitude of high streamflow events (Pearson et al., 2011; Wildman and MacBroom, 2005). Downstream of the removed dam, geomorphic response is a function of the post-dam streamflow regime and the sediment delivery from upstream sources, including impounded reservoir sediments (Doyle et al., 2003a; Ferrer-Boix et al., 2014; Pizzuto, 2002). The typical initial release of fine sediment can fill pools and bury coarse-grained riffles, resulting in homogenizing riverbed morphology and sediment type (Pizzuto, 2002). Coarse sediment delivery from upstream may be delayed and will depend on the occurrence of streamflow events of sufficient discharge magnitude to
mobilize coarse sediment; however flushing of fine sediments and deposition of coarser sediments downstream of the removed dam can increase topographic heterogeneity of the riverbed (Kibler et al., 2011). After the short-term development of deposits, continued channel evolution will occur as the deposits are episodically mobilized during high flow events or by transport of bedload through dispersion and/or translation (Grant and Lewis, 2015; Major et al., 2012; Pizzuto, 2002).

Much of the work on geomorphic response following dam removal has focused in non-urban settings (Bushaw-Newton et al., 2003; Cheng and Granata, 2007; Doyle et al., 2003a; Kibler et al., 2011), and there is lack of and an increasing need for understanding the geomorphic responses within an urban setting (Roberts et al., 2007; Rumschlag and Peck, 2007). Urbanization affects hydrological and sediment regimes and stream geomorphology by increasing the total amount of runoff and reducing the time to peak discharges in the hydrograph as a result of the increase in impervious surfaces (Gurnell et al., 2007; Paul and Meyer, 2001). In addition, riparian corridors and floodplains can be limited in spatial extent as a consequence of adjacent urban and suburban activities including roads and buildings (Richardson et al., 2007). Channel banks may be armored to minimize erosion, channel migration, which often translates to property loss (Riley, 1998). Finally, multiple dams or other in-channel engineering structures may exist in sequence in rivers flowing through urban or suburban landscapes. Dam removal in an urban setting, within the context of these additional external influences on channel morphology and geomorphic adjustment, provides a unique setting to examine geomorphic response after lowhead dam removal.
Dam removal studies commonly use repeat cross-sectional surveys to report the geomorphic responses (e.g., Burroughs et al., 2009; Cannatelli and Curran, 2012; Harris and Evans, 2014; Stanley et al., 2002), but these surveys are limited in their ability to capture the larger spatial variability of potential change in streambed topography within a reach-scale portion of a river. Acoustic Doppler current profilers (ADCP) capture high resolution, spatially extensive hydrogeomorphic data. ADCPs have been conventionally used to measure discharge and 3-D flow fields (Flener et al., 2015; Gordon, 1989; Jamieson et al., 2011; Mueller and Wagner, 2009; Oberg and Mueller, 1994), but are increasingly used to characterize channel bathymetry (Cheng and Granata, 2007; Dinehart and Burau, 2005; East et al., 2015; Williams et al., 2015). Using an ADCP to collect geomorphic data following a dam removal could provide unique insights into reach-scale geomorphic channel adjustments.

This study reports on geomorphic adjustment of two mid-sized, urban rivers to lowhead dam removal in the two to three years following dam removal. In September of 2012, a 2.4-m high lowhead dam was demolished on the Olentangy River, Columbus, Ohio, USA. Approximately one year later, in November 2013, a 4.1-m high lowhead dam was removed approximately 5 river kilometers (rmk) downstream on the Scioto River, to which the Olentangy River is tributary. Both dams were over 70 years old and no longer functioned for their original purposes; the Olentangy River dam provided cooling water for a now inactive power plant and the Scioto River dam had been built for flood control and aesthetics in the downtown area. Both sections of rivers flow through highly urbanized areas with limited riparian corridors thus providing an opportunity to evaluate geomorphic adjustment in this relatively unstudied setting. Repeat ADCP surveys over
short time intervals (~3 month intervals) allow for detailed tracking of geomorphic adjustment and short-term channel evolution. Much like dam construction, dam removal can create a disturbance to the river system (Tullos et al., 2014). Therefore, consistent with geomorphic adjustment to disturbance (Simon, 1989), river response immediately following dam removal was expected to be rapid, reducing in magnitude with increasing time since removal (Pearson et al., 2011; Tullos and Wang, 2014). The character of short-term response at least in part determines physical-biotic response characteristics over longer time-scales (Stanley and Doyle, 2003). Therefore it is critical to document geomorphic changes within the first few years after dam removal as a critical component to understanding longer-term geomorphic-response and associated ecological-response trajectories.

This study uses paired control-treatment design to quantify the geomorphic response of stream channel reaches above and below a removed run-of-river, lowhead dam, in comparison with reaches adjacent to existing run-of-river, lowhead dams. The overarching research objectives are to 1) quantify adjustments in channel bed morphology and substrate characteristics in the first three years following dam removal on the Olentangy River and the first two years following dam removal on the Scioto River and 2) place observed channel adjustment in an urban system within the context of other dam removal projects.
2.1.1 Hypotheses

I hypothesize that river reaches upstream of the removed dam will demonstrate an overall increase in topographic heterogeneity and sediment coarsening as a result of erosion into impounded sediments. Reaches downstream of removed dams are expected to experience initial aggradation and fining as a consequence of anticipated deposition of formerly impounded sediments. Expected deposition is anticipated to reduce riverbed topographic heterogeneity in downstream reaches. The initial aggradation, sediment fining, and reduction in topographic heterogeneity is expected to occur within the first few months after dam removal and will not be captured within the study period. With increasing time following dam removal, downstream reaches are expected to coarsen and heterogeneity in riverbed topography will increase as patches of recently deposited sediment erode and are transported downstream. I test these hypotheses through analyses of repeat bathymetric surveys and near-surface riverbed substrate at several time periods following dam removal. Repeat bathymetric surveys allow for comparison of erosion and deposition patterns, development and evolution of in-channel macrofeatures, and reach-scale metrics of heterogeneity. The hypotheses are applicable to both the Olentangy and Scioto River study reaches.
2.2 Regional Setting

Land use in the Olentangy (1,400 km² drainage area) and upper Scioto Rivers (4,220 km² drainage area) is dominated by agriculture, but the study reaches are located within an urban landscape (Figure 2.1). Both rivers flow for several kilometers through Columbus, Ohio, an urban city with a population of approximately 787,000 (US Census 2010). The Olentangy River flows into the Scioto River at approximately rkm 222 in downtown Columbus, Ohio. The Scioto River continues southward into the Ohio River at the Ohio-West Virginia state line.

A series of lowhead, run-of-river dams occur along the Olentangy and Scioto Rivers to serve as flood control, recreational use, water supply, and to cover sanitary sewer lines. Flow within the lower portion of the Olentangy River is also regulated by the 28-m high Delaware dam located approximately 50 km upstream of the removed 5th Avenue dam. There are no lowhead dams between the removed dam on the Olentangy River and the confluence with the Scioto River. Flow within the study reaches on the Scioto River is regulated by two larger dams (16 m and 24 m high) located 11 and 27 km upstream of the Olentangy River confluence, in addition to the Delaware dam on the Olentangy River. Several additional lowhead dams occur upstream within the watershed; a single lowhead dam exists downstream of the removed dam on the Scioto River before the Ohio River confluence.
Figure 2.1 The Olentangy River and Scioto River study area in Columbus, Ohio. The Olentangy R. is a 5th order tributary of the 6th order Scioto R. Pictures are from after dam removal; pictures for OR1-3 and SR2-3 are facing upstream and for OR4 and SR1 are facing downstream. Dams represented by a single line are existing dams (Dodridge St. and Greenlawn Ave. dams; dams represented by a double line are removed dams (5th Ave. and Main St. dams). In this context, “control” refers to a reach adjacent to an existing lowhead dam. Figure adapted from Dorobek et al., 2015.
Both the Olentangy and Scioto Rivers within the study reaches are single thread, meandering channels with narrow riparian corridors. Average channel widths along the study reaches are between 37 and 42 m for the Olentangy River and 95 and 133 m for the Scioto River. The river channel gradient is 0.76 m/km on the Olentangy River and 0.48 m/km on the upper Scioto River (USGS, 2016) with even lower water surface gradients recorded in the study reaches.

This area has a mean annual precipitation of 93 centimeters (cm) (USGS, 2016), mostly falling as rain. Summers are hot and humid, and winters are relatively mild. Streamflows are highest in the winter and early spring (Dec-April) with late summer-early autumn baseflows (Figure 2.2). The apparent disparity between precipitation and streamflow discharge, notably the absence of peak streamflows during seasonal precipitation maximums in spring-early summer is attributed to the regulation of the 28-m high Delaware dam located approximately 50 rkm upstream of the Olentangy River study reaches. Mean annual discharge is 14 cubic meters per second (m$^3$/s) in the Olentangy River and 43 m$^3$/s in this upper region of the Scioto River. Streamflow magnitudes with an approximate 2-yr recurrence interval (RI) is 259 m$^3$/s in the Olentangy River and 627 m$^3$/s in the Scioto River (USGS, 2016).

The lack of forest cover in these watersheds and high percentage impervious surfaces in the urban areas may cause sudden high flow events which transport sediment-rich runoff into rivers (Brabec et al., 2002; Poff et al., 1997). The larger dams, such as the Delaware dam, can lessen the effects of sedimentation downstream by acting as a sediment sink. In the past 50 years, the Delaware dam impoundment has lost
approximately 15% of its storage capacity. Delaware dam is a bottom release dam; sediment that has settled out is released downstream (Friends of the Lower Olentangy Watershed, 2003).

Figure 2.2 Average monthly precipitation and discharge for the lower Olentangy R. (solid line) and upper Scioto R. (dashed line) watershed. Precipitation data is 30 year (1981-2010) monthly norms from the NOAA National Centers for Environmental Information climate station at Columbus Ohio State University Airport, OH US. Discharge data are monthly statistics from 1981-2010 from USGS gage 03226800 Olentangy R. near Worthington, OH (15 rkm upstream of removed 5th Avenue dam) and USGS gage 03227500 Scioto R. at Columbus, OH (6 rkm downstream of the removed Main Street dam).
2.2.1 Study Design

This study includes repeat surveys of four reaches along the Olentangy River (OR) and three reaches along the Scioto River (SR) (seven total) (Figure 2.1, Table 2.1). Study reaches are numbered in the downstream direction and categorized based on their locations to either an existing (control) or a removed (experimental) lowhead dam. The four study reaches on the Olentangy River include one control reach upstream of an existing dam (OR1), two experimental reaches (OR2, OR3) upstream of the removed dam, and one experimental reach (OR4) downstream of the removed dam. The three study reaches on the Scioto River include one control reach downstream of an existing dam (SR3), one experimental reach (SR1) upstream of the removed dam, and one experimental reach (SR2) downstream of the removed dam. In addition, active restoration occurred upstream of removed dams and are represented by OR3 and SR2.

On the Olentangy River, a 2.6-rkm portion of the river was actively restored, which will allow for comparison of geomorphic conditions with a passively-restored reach (OR2) also upstream of the removed 5th Avenue dam. The active restoration of the Olentangy River included regrading the riverbed in pool and riffle sequences, installation of in-channel structures to promote pool scour, and creation of vegetated floodplain and wetland pockets along channel margins. Engineering activities along portions of the former dam impoundment on the Scioto River occurred as well, but the activities focused on the construction and reinforcing of the channel banks for green space and recreational use in the downtown area. The particular combination of reaches across two rivers is a consequence of limitations of available, appropriate study sites, but still allows for
upstream and downstream comparisons of river reaches between existing and removed
dam scenarios and comparisons between reaches with in-channel and floodplain
restoration and those with no active restoration.

2.2.1.1 Site specific conditions

The Olentangy River contains four of the seven study reaches: upstream control,
upstream treatment, upstream treatment with active restoration, and downstream
treatment (Figure 2.1). OR1 is located immediately upstream of a 2.0-m high run-of-river
dam (Dodridge Street dam) and is characterized by a large, gentle meander. OR2 and
OR3 are located 2.3 rkm and 1.3 rkm upstream of the removed 5th Avenue dam,
respectively. Both of these reaches are located within or partially within the former 2.7-
rkm long upstream impounded region created by the 5th Avenue dam. OR3 is located
within the actively restored portion of the river. OR4 is located approximately 0.4 km
downstream of the removed 5th Avenue dam. Bridge crossing and footings occur
immediately upstream of OR3 and immediately upstream and within OR4.

The Scioto River contains three of the seven study reaches: upstream treatment
with active restoration (SR1), downstream treatment (SR2), and downstream control
(SR3) (Figure 2.1). SR1 is located approximately 0.9 km upstream of the removed Main
Street dam. This reach is located within the former 3.7-rkm long upstream impounded
region created by the Main Street dam and the restored portion of the river. SR2 is
located approximately 0.3 km downstream of the removed Main Street dam. SR3 is
located approximately 1 km downstream of a 3.4 m high run-of-river dam (Greenlawn
Avenue dam) and is characterized by a large sediment bar in the upstream river left
portion and riffles at the upstream and downstream portion. Bridge crossings and footings occur within an immediately downstream of SR1 immediately upstream and downstream of SR2. Footings of a demolished bridge occur immediately upstream of SR3 in the sediment bar.

The study reaches are within a highly urbanized area, which limits the spatial extent of the floodplain and the ability of the channel to migrate thus its channel sinuosity. Average length for each study reach is 450 ± 95 m (Table 2.1). All reaches on the Olentangy River are wadeable at low flows with the exception of OR1. Reaches on the Scioto River are not wadeable, which have average depths of 1.85 ± 0.45 m (Table 2.1). The study reaches have an urbanized riparian corridor with narrow and limited vegetated floodplains. Most reaches have some forested riparian buffer (approximately 20-50 m wide), but are severely constrained by suburban and urban development.
Table 2.1 Summary table of study reach conditions. Rkm is the river kilometer to the approximate midpoint of the study reach. Mean channel widths and depths are calculated from the bathymetry surveys using an acoustic Doppler current profiler (ACDP) data from June 2015 sample period when discharge (Olentangy R. USGS gage 03226800, Scioto R. USGS gage 03227500) was closest to the rivers’ mean annual flow of 14 m$^3$/s and 43 m$^3$/s, respectively. Flow conditions were approximately 13 m$^3$/s on the Olentangy R. and ranged from 20-40 m$^3$/s over the three days of surveying on the Scioto R., which was each Scioto R. reaches’ highest discharge recorded from the collected surveying times. Channel width is reported as wetted width from ADCP points within transects. There is variation in reach length because repeat surveys did not overlap exact same portion of reach; for example, surveys would extend further up or downstream in comparison to other surveys.

<table>
<thead>
<tr>
<th>River</th>
<th>Reach</th>
<th>Reach Conditions</th>
<th>Rkm</th>
<th>Mean Reach Length (m)</th>
<th>Mean Channel Width (m)</th>
<th>Mean Depth (m)</th>
<th>Maximum Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olentangy</td>
<td>OR1</td>
<td>upstream of existing dam</td>
<td>6.8</td>
<td>370 ± 40</td>
<td>42 ± 4</td>
<td>1.38 ± 0.70</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>OR2</td>
<td>upstream of removed dam; passive restoration</td>
<td>5.6</td>
<td>410 ± 65</td>
<td>44 ± 2</td>
<td>0.59 ± 0.28</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>OR3</td>
<td>upstream of removed dam; active restoration</td>
<td>4.6</td>
<td>420 ± 30</td>
<td>42 ± 3</td>
<td>0.84 ± 0.36</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>OR4</td>
<td>downstream of removed dam</td>
<td>2.5</td>
<td>480 ± 25</td>
<td>37 ± 5</td>
<td>1.06 ± 0.59</td>
<td>3.81</td>
</tr>
<tr>
<td>Scioto</td>
<td>SR1</td>
<td>upstream of removed dam; restoration</td>
<td>214.3</td>
<td>645 ± 90</td>
<td>95 ± 17</td>
<td>1.45 ± 0.88</td>
<td>5.59</td>
</tr>
<tr>
<td></td>
<td>SR2</td>
<td>downstream of removed dam</td>
<td>212.7</td>
<td>375 ± 15</td>
<td>122 ± 14</td>
<td>2.33 ± 1.02</td>
<td>4.67</td>
</tr>
<tr>
<td></td>
<td>SR3</td>
<td>downstream of existing dam</td>
<td>209.5</td>
<td>415 ± 15</td>
<td>133 ± 11</td>
<td>1.77 ± 0.87</td>
<td>4.42</td>
</tr>
</tbody>
</table>
2.3 Methods

2.3.1 Field Sampling and Data Post-Processing

Field data collection included repeat topographic surveys and sediment grain-size characterizations at all study sites. Six to eight bathymetric and velocity surveys were completed using an ADCP on the Olentangy River over the three-year (2013-2015) study period. Three to four bathymetric were completed using an ADCP on the Scioto River over the two-year (2014-2015) study period. Sediment samples occurred at the same time for most of these surveys. In addition, four channel elevation surveys of two riffles on the Olentangy River at OR3 and OR4 were conducted using a total station in the second and third years of the study (Table 2.2). Bathymetric surveys and sediment samples began 10 months after each dam removal, in June of 2013 and September of 2014, respectively, and were conducted every two to seven months until August of 2015. Surveys were typically conducted twice a year, once in the late spring or early summer then again in autumn.

There were a few instances in which data were not collected during a sample period. In particular, data from the April 2014 bathymetric survey are not included for OR3 because of GPS quality issues discovered during post-processing. Sampling on the Scioto River in June 2014 was not possible due to timing of high flows and availability of time-limited access to survey equipment. Reaches OR2 and SR1 have an additional bathymetric survey and sediment samples from December 2014; surveying could not be completed for the rest of the reaches because of issues survey equipment. Results and analysis will not include these December 2014 ACDP surveys and sediment samples,
unless otherwise stated. Sediment samples were not collected at OR3 in September 2013 or at any reach in June 2014.

Elevation surveys of the select riffles began in August 2014 and occurred at four to six month intervals that included November 2014, May 2015, and September 2015.
Table 2.2 Inventory and time of field sampling. The Sediment column indicates which method was used to collect the sediment samples for that sample period. Dec 2014 is italicized because it was an incomplete sample period and will not be included in results or data analysis. Month and year in parentheses for Riffle indicate the time when the total station (TS) survey was conducted on the select riffle or sediment bar within that reach. Restoration in OR3 and SR1 occurred from approximately August 2012 through late Winter 2014 and November 2013 thru November 2015, respectively.

<table>
<thead>
<tr>
<th>River</th>
<th>Reach Description</th>
<th>Sample Period</th>
<th>ADCP</th>
<th>Sediment</th>
<th>Riffle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olentangy</td>
<td>OR1 upstream control</td>
<td>June 2013</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sept 2013</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April 2014</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>June 2014</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sept 2014</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>June 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR2 upstream, passive restoration</td>
<td>June 2013</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sept 2013</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April 2014</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>June 2014</td>
<td>X</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Sept 2014</td>
<td>X McNeil</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>June 2015</td>
<td>X McNeil</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Aug 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR3 upstream, active restoration</td>
<td>June 2013</td>
<td>X shovel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sept 2013</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April 2014</td>
<td>X shovel</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>June 2014</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Dec 2014</td>
<td></td>
<td></td>
<td>TS (Nov 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>June 2015</td>
<td>X McNeil</td>
<td></td>
<td>TS (May 2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 2015</td>
<td>X McNeil</td>
<td></td>
<td>TS (Sept 2015)</td>
</tr>
<tr>
<td></td>
<td>OR4 downstream</td>
<td>June 2013</td>
<td>X shovel</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Sept 2013</td>
<td>X shovel</td>
<td></td>
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<td></td>
<td></td>
<td>April 2014</td>
<td>X shovel</td>
<td></td>
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<td></td>
<td></td>
<td>June 2014</td>
<td>X</td>
<td></td>
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<td>Dec 2014</td>
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<td>X McNeil</td>
<td></td>
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<td></td>
<td></td>
<td>Aug 2015</td>
<td>X McNeil</td>
<td></td>
<td>TS (Sept 2015)</td>
</tr>
<tr>
<td>Scioto</td>
<td>SR1 upstream, restoration</td>
<td>Sept 2014</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dec 2014</td>
<td></td>
<td></td>
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<td></td>
<td>June 2015</td>
<td>X McNeil</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Aug 2015</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR2 downstream</td>
<td>Sept 2014</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
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<td>June 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR3 downstream control</td>
<td>Sept 2014</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>June 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug 2015</td>
<td>X McNeil</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3.1.1 Repeat bathymetric surveys

Bathymetric surveys were completed using an ADCP (Sontek M9 RiverSurveyor) (Figure 2.3). The ADCP is a multi-beam sensor that allows for spatially dense observations of channel depth, bathymetry, and velocity (Sontek, 2014). The M9 ADCP is equipped with eight transducers (four 3-MHz and four 1.0-MHz) for water velocity profiling and a 0.5 MHz vertical beam transducer for depth. Maps of river bathymetry are georeferenced such that repeat surveys can be differenced from each other to quantify magnitude and spatial character of geomorphic change through time (Wheaton et al., 2010; Williams et al., 2015).

![Figure 2.3 Setup of the ADCP base station and hydroboard. Base station was placed in a location on the river bank that maximized line-of-site visibility throughout the extent of the survey reach.](image)

Measurements were collected at informal cross sections (e.g., not-monumented on the river bank) spaced approximately 10-15 m apart and three longitudinal profiles along the channel margins and middle of the river channel (Figure 2.4). The ADCP was
mounted on a SonTek hydroboard and either attached to the bow of a kayak or towed behind a kayak, which was paddled at equal to or less speeds relative to the river velocities. Each survey point was GPS referenced (WGS 84 horizontal datum) with the SonTek differential GPS (D-GPS) mounted on the ACDP and a corresponding SonTek real-time kinematic (RTK) base station mounted on a tripod; GPS quality ranged from RTK (< 3cm) to differential (< 1 m) to standard (> 1 m); measurement accuracy of transducers was 1% of the depth. This system has a depth profiling range of 0.2 to 80 m. All surveys were collected during low flow conditions.

Figure 2.4 Example of typical ADCP survey with cross-sections spaced 10-15 m apart and three longitudinal profiles. ADCP points for OR4 June 2015 survey.
ADCP data was exported from RiverSurveyor recording software to ArcGIS using GPS-GGA as track reference. GGA refers to the NMEA-0183 protocol for outputting GPS position of the ADCP unit; this reference was chosen based on visual inspection and comparison with other GPS references. The data points for each study reach and sample period were post-processed to only include points with HDOP (horizontal dilution of precision; describes the geometric strength of satellite configuration on GPS accuracy at particular time and location) greater than 0 but less than 6, four or more satellites, and depth measurements greater than 0 m (Sontek, 2014). The minimum profiling range for the ADCP is 0.20 m, and measurements reported as 0 m could be any depth less than 0.20 m; therefore, these points were removed from analysis. Points were removed if they occurred in dense clusters, such as when the hydroboard was first launched or when paddling had temporarily paused for when paddlers switched or needed a short break. Points were also removed if they extended upstream or downstream of the reach’s general areas overlap or near bridges. Stream bottom elevations were calculated by subtracting measured depth from the calculated water surface elevation.

2.3.1.1.1 Water surface elevations

During post-processing, the water surface elevations collected for each point were found to be not consistent or accurate; one reach surveying would often have multi-meter differences in water surface elevations even though no such changes occurred during surveying. These values were necessary for determining the elevations of the stream bottom. A recent study by Muirhead and Annable (2014) found that since the SonTek M9
ADCP, base station, and RiverSurveyor software cannot be georectified to geodetic benchmarks, the water surface elevations are acquired relative to an arbitrary vertical datum and are not considered globally accurate (Muirhead and Annable, 2014); therefore, the vertical water surface elevation measurements may not be accurate for comparison of repeat surveys over time.

Water surface elevations from USGS-operated streamflow gages in the Olentangy and Scioto Rivers were used as a proxy for water surface elevations during each survey. Water surface elevations are collected at 15- or 30-minute intervals and are accurate to within 3 mm (Hirsch and Costa, 2004). For the Olentangy River, we used water surface elevations recorded at a streamflow gage located 1 rkm upstream of the removed dam, 03227107 at J H Herrick Dr at Columbus, OH (from here on referred to as JHerrick), which came into operation in January 2015, 18 months after the start of the study. Using a linear relationship between the JHerrick gage and the next nearest USGS gage, 03226800 near Worthington, OH (from here on referred to as Worthington), which is located ~15 rkm upstream of the removed dam, we estimated water surface elevations for ADCP surveys. No major tributaries enter the Olentangy River between these two gages or within the study reaches. A linear trend was computed for the mean daily discharges at the two streamgage stations using mean daily values from 281 days (Jan. 15 2015 – Oct. 6, 2015) (Figure 2.5). The average discharge during the ADCP survey time at a reach was determined using instantaneous discharge readings collected every 15-30 minutes from the Worthington gage. The linear trend was then applied to the mean Worthington discharge to determine the discharge at the JHerrick gage. The USGS stage-discharge rating curve for the JHerrick gage was used to determine the gage height from the
discharge. This gage height was converted to water surface elevation; at a gage height of 0 m, water surface elevation is 214.84 m. An elevational difference was applied to the gage water surface elevation depending on the reach, based on a 0.0005 m/m slope; for example, for all OR2 ADCP surveys, 0.70 m was added to the JHerrick water surface elevation since the midpoint of the reach is located 1,390 m upstream of the gage.

Figure 2.5 Linear relationship between the mean daily discharges (cubic feet per second) recorded at the Olentangy USGS gages 03226800 at Worthington and 03227107 at JHerrick. Worthington gage is located 15 rkm upstream of removed 5th Avenue dam and JHerrick gage is located 1 rkm upstream of the removed dam.

The water surface elevations on the Scioto River sites were determined using USGS gage 03227500 Scioto River at Columbus, Ohio, located 6 rkm downstream of the
removed Main Street dam and 2.5 rkm downstream of SR3. Again, no major tributaries enter the Scioto River with the study reaches. The stage-discharge rating curve for this gage was used to determine the gage height from the average discharge during the ADCP survey time at a reach and an elevational difference was applied depending on the reach. Reach elevational differences took the height of existing dams into account when necessary.

Water surface elevations were collected using a Leica GNSS RTK system (< 3-cm accuracy) during the August 2015 sampling to verify that water surface slopes within each reach were negligible. Change in stage during an ADCP surveying was also assumed to be negligible. This assumption was verified by comparing the streamgage discharge standard deviations within a reach survey period with the corresponding gage height standard deviations from the stage-discharge rating curve. The ranges of discharge standard deviations and corresponding stage height standard deviations are summarized in Table 2.3. The majority of ADCP surveys were conducted during times where the discharge standard deviation was less than 1 m³/s (Figure 2.6).
Table 2.3 Sampling of the ranges of discharge standard deviations and corresponding stage height standard deviations during an ADCP survey. The last row is the maximum standard deviation recorded during the study period on that river.

<table>
<thead>
<tr>
<th></th>
<th>Olentangy R.</th>
<th>Scioto R.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Discharge standard deviation (m³/s)</td>
<td>Stage standard deviation (m)</td>
</tr>
<tr>
<td>low</td>
<td>0.03</td>
<td>&lt; 0.01 (0.003)</td>
</tr>
<tr>
<td>intermediate</td>
<td>0.36</td>
<td>&lt; 0.01 (0.009)</td>
</tr>
<tr>
<td>maximum</td>
<td>3.83</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 2.6 Frequency of discharge standard deviations during a single reach ADCP survey. The largest discharge standard deviation was 3.83 m³/s, which corresponds to gage height standard deviation of 5 cm; this occurred for only a small portion of an ADCP reach survey.
2.3.1.1.2 Reach-scale bathymetric surface generation

Bathymetric surfaces were generated at 1x1-m resolution in ArcGIS v10.2 (ESRI, 2014) using the Geostatistical Analyst Geostatistical Wizard tool. Point data of stream bottom elevation was interpolated using ordinary isotropic kriging by fitting a model (either circular, exponential, or exponential based on calculated root mean square error) to the generated semivariogram (Johnston et al., 2001). Surfaces were generated within a mask, which bounded the extents of the ADCP points within the river channel; each survey had a unique mask. Anisotropic kriging, which takes directionality into account, is commonly used when interpolating river bathymetric surfaces (Legleiter and Kyriakidis, 2008; Merwade, 2009; Williams et al., 2015), but is applicable to use when the river channel is straight while in Cartesian coordinate system or has been converted to streamwise coordinate system. Nearly all the reaches of this study had a slight meander or bend, which made using anisotropic kriging to model stream bottom elevations not an ideal interpolation technique. Comparisons of isotropic and anisotropic kriging in Cartesian coordinate systems found that isotropic kriging performs better when modeling river channel bathymetry (Merwade et al., 2006).
2.3.1.2 Sediment samples

Surface and near surface sediment samples were collected at each reach using a spade shovel or a McNeil sampler. Two shovel or McNeil core samples were collected and aggregated in the wadeable margins at the upstream, middle, and downstream region of each reach, yielding three samples per reach. A shovel was used for sediment collection for the first three sample periods (June and September 2013 and April 2014); the McNeil sampler was used for the following sample periods. Field and laboratory comparisons of McNeil and shovel substrate samples show little to no significant difference in composition between the two sampling methods (Grost et al., 1991; Young et al., 1991). The McNeil sampler (McNeil and Ahnell, 1964) is a stainless steel cylindrical collection basin with a smaller inner 10-cm diameter, 15-cm long coring cylinder attached at the bottom; our sampler was manufactured by Rickly Hydrological Company based in Columbus, OH (Figure 2.7). The coring cylinder was pushed into the streambed material by pressing on the handle of the larger, outer collection basin while rotating the sampler back and forth until the bottom of the collection basin was at least within 3 cm of the streambed. Sediment in the coring cylinder was removed by hand and stored in the outer lip inside the collection cylinder. Once the coring cylinder was empty, the sampler was carefully removed from channel. All sediment was transferred from the collection cylinder and rinsed with river water into a plastic storage bin in the field; excess water was drained from the bin. Efforts were made to prevent loss of sediment that had settled out of suspension by placing the lid on the plastic bin while draining off excess water, but sediment in suspension were likely poured off. If a minimum of 12 cm of the coring cylinder could not be fully inserted into the streambed material for a given
sample, the sampler and any collected sediment was removed and a new sample was taken in that area.

All samples were transferred from the plastic storage bins to aluminum pans and thoroughly dried in ovens at 70 C or air dried in open air green houses for several weeks. The dried sediment samples were thoroughly hand mixed, sub-sampled in half, and sieved through 12.5-, 4.75-, and 2.0-mm sieves and weighed using a Mettler PH4000 scale. Sediment retained on the 12.5-mm sieve, excluding organic material such as wood or shells, was sorted through a gravelometer to size clasts of the coarser sediment and weighed again.

Figure 2.7 McNeil sediment sampler use and dimensions. The coring portion of the sampler is 10 cm in diameter and can be inserted a maximum of 15 cm into the streambed. The collection basin is 30 cm in diameter and 46 cm tall. McNeil diagram provided by Rickly Hydrological Company.
2.3.1.3 Elevation surveys of riffles

Repeat elevation surveys were conducted at a riffle within two of the three experimental reaches on the Olentangy River. These areas are too shallow to be surveyed by the ADCP but are regions of potential significant geomorphic change. The riffles surveyed in the upper portion of OR3 and OR4 developed after the dam removal.

Elevation surveys were conducted using a Gowin TKS-202 total station (0.5mm/100m accuracy), prism rod, and handheld GPS unit (Garmin eTrex HC series, <10m accuracy). Benchmarks were established at each riffle and collected using the total station during each survey. Elevation surveys included two to three cross sections at the upstream, middle and downstream extent of the riffle and one to three longitudinal surveys along the thalweg and on either side of the thalweg. Surveyed riffles were generally 60 m long. Elevation was measured at approximately 1-2 m intervals and obvious changes in slope.

Although riffles were repeatedly surveyed, exact locations of cross-sections and longitudinal profiles were not repeatedly surveyed. The original intent of these surveys was to join them to bathymetry maps from the ADCP surveys instead of conventional repeat cross section and longitudinal profile survey analysis. Repeat cross section and longitudinal profiles in close proximity (e.g. 2-3 m distance) to each other were compared to characterize change through time. The similar profiles were compared for local and reach slope and profile plotting. Similar profiles were limited in length upstream and downstream by the profile that extended the least in either direction.
2.3.2 Data Analysis

2.3.2.1 Bathymetry

2.3.2.1.1 DEM of difference to evaluate patterns of sediment transport and development of channel macro features.

Change in stream-bottom elevation between surveys was evaluated by constructing a DEM of difference (DoD). The DoDs map the spatial distribution and amount of deposition and erosion within the stream channel. Probabilistic thresholding was used to determine which elevation changes were statistically noticeable geomorphic changes as opposed to model noise (Brasington et al., 2003; Williams et al., 2015). The errors associated with the two DEMs can be approximated with the standard deviation error (SDE) surfaces associated with each interpolated bathymetric surface. The critical threshold error, $U_{crit}$, surface for each DoD is calculated using equation:

$$U_{crit} = t \sqrt{SDE_1^2 + SDE_2^2}$$

where $t$ is the two-tailed Student’s $t$ distribution for a given confidence interval; we used a 68 percent confidence interval, or 1 standard deviation, and $t = 1.0$ (Lane et al., 2003; Milan et al., 2011; Williams et al., 2015). This was done on a cell-by-cell basis using ArcGIS Raster Calculator tool. The raw DoD surfaces were calculated using Raster Calculator, where

$$DoD_{2-1} = DEM_2 - DEM_1$$

DEM$_1$ refers to the bathymetric surface which occurs chronologically first (e.g. June 2013) and DEM$_2$ refers to the surface that is chronologically second in time (e.g.
September 2013) relative to the two survey times used to calculate a given DoD. Any elevation change in the raw DoD which was greater than the $U_{\text{crit}}$ surface value is considered to be statistically noticeable geomorphic change (true if “$U_{\text{crit}} > \text{DoD}$” for deposition or “$- U_{\text{crit}} < \text{DoD}$” for erosion at a given raster cell).

2.3.2.1.2 Reach-scale metrics of heterogeneity

A variety of metrics can be used to quantify topographic heterogeneity, each uniquely describing spatial complexity (described in Scown et al., 2015). The DEM Surface Tools ArcGIS add-in (Jenness, 2012, 2004) was used to compute and generate surfaces of total curvature and 3-D surface area from the bathymetric DEM surfaces. The surface metrics standard deviation of elevation, mean rugosity, standard deviation of curvature, and elevation range were calculated within a specified search radius or scale (5, 10, 20, and 50 m) for each cell of the input surface using the ArcGIS Focal Statistics tool. The 3-D surface area of each cell was summed to obtain a total 3-D surface area of the reach at a given time period, and 2-D area of the reach was equal to the total number of cells (each 1-m$^2$) in the surface area raster; reach-scale rugosity was calculated as the ratio of total 3-D area to total 2-D area (Brasington et al., 2012). The reach-scale distribution of stream bottom elevation values in the DEM was described by computing the skewness and kurtosis for each reach and time period using the moments R package (Komsta and Novomestky, 2015). The metrics used in this study are described in Table 2.4.

A combination of univariate and multivariate statistical methods were used to examine the geomorphic difference within the reaches between time periods. For the
within-reach metrics (standard deviation of elevation, mean rugosity, standard deviation of curvature, and elevation range), correlations were run on a subset of reaches, survey time periods, and scales; the correlation matrices using Spearman’s ρ and visualization of box plot distributions were used to determine if any of the metrics were highly correlation and should be removed from analysis. A subset of each reach was created by using fixed, repeated points spaced at least 10 m apart and extracting the metric value from the within-reach metrics surfaces for each time period (Table 2.5). If the extent of a survey at a given time period did not include one of the fixed points, an NA value was given.

Univariate statistical analysis of the Olentangy and Scioto River reaches was conducted with a linear mixed model to assess changes in topographic heterogeneity over time within each reach; this was conducted using the lmer function in the R statistical package lme4 (Bates et al., 2015). All values were first log transformed to improve normality. Time, in months since the first survey, was the fixed effect with time and fixed-point ID assigned as random effect (intercept and slope). For all reaches and metrics, the coefficient for the fixed effect (time) are reported with standard error and p-values.

Multivariate statistical analysis of reach-scale metrics (rugosity, skewness and kurtosis of elevation, standard deviation of elevation, and standard deviation of curvature) on the Olentangy and Scioto River reaches was conducted in nonmetric multidimensional scaling (NMDS) to identify potential differences between reaches. The NMDS method is useful in visualizing the structure of communities, in this case reaches, based on environmental variables, such as metrics of heterogeneity. The NMDS analysis
was also chosen because it has no assumptions for data normality or linearity. Correlations among the five reach-scale metrics were completed using Spearman’s coefficient. Metrics measurements were mean centered by each reach prior to analysis to account for the repeated measures over time and to eliminate spatial autocorrelation. NMDS was performed using the vegan package function metaMDS (Oksanen, 2015). Minimum stress, which is a measure of goodness-of-fit, for two dimensions was computed. Vectors, which are the reach-scale metrics, were fitted to the ordination using the envifit function; individual vector significance was evaluated with 999 permutations. A nonparametric permutational multivariate analyses of variance (PerMANOVA) via the adonis function in vegan package was then used to test for significance between reaches and time periods; Euclidean was the distance measure and 999 permutations were used.
Table 2.4 Metrics used for analysis of generated DEM reach surfaces.

<table>
<thead>
<tr>
<th>Surface metric</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation of elevation (m)</td>
<td>the extent of variation around a mean elevation; low value indicates little heterogeneity while high value indicates larger heterogeneity within a specific scale</td>
</tr>
<tr>
<td>Rugosity (m²/m²)</td>
<td>a measure of topographic roughness, which is the ratio of 3-D area (surface area) to 2-D area (planimetric area); values typically range from 1.0 - 1.1 for shallow fluvial topography (Brasington et al., 2012)</td>
</tr>
<tr>
<td>Standard deviation of curvature (radians/m)</td>
<td>describes how variable the curvature of a surface is within a specific scale around a mean curvature</td>
</tr>
<tr>
<td>Elevation range (m)</td>
<td>the difference between the highest and lowest elevation within a specific area describes the magnitude of relief</td>
</tr>
<tr>
<td>Skewness</td>
<td>describes peak and valley characteristics as a function of the distribution of surface elevations; positive value indicates the presence of high peaks or shallow valleys; negative value indicates the presence of deep valleys or flattened peaks</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>describes reach evenness as a function of how peaked the distribution of surface elevations is; high values indicate the presence of a dominant elevation; low values indicate a smoother surface</td>
</tr>
</tbody>
</table>
Table 2.5 Example of data layout after extracting metric values; this example are for the first 20 points at reach OR4 standard deviation of elevation within a 5-m radius. An NA value indicates that the specific point was not within the extent of the survey at a particular time period.

<table>
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<th>Elev.sd.2</th>
<th>Elev.sd.3</th>
<th>Elev.sd.4</th>
<th>Elev.sd.5</th>
<th>Elev.sd.6</th>
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<td>0.112</td>
<td>0.054</td>
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</tr>
<tr>
<td>or4.18</td>
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<td>0.129</td>
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<td>or4.19</td>
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<td>0.041</td>
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<td>or4.20</td>
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<td>0.032</td>
<td>0.039</td>
<td>0.057</td>
</tr>
</tbody>
</table>

2.3.2.2 Sediment

Sediment weights of the three samples (upstream, middle, downstream) per reach were added together to present reach-scale characteristics and changes (Tullos and Wang, 2014). Using the measured weights, proportion of total weight and cumulative percent finer were computed for sand, gravel, and cobble size clasts (2.0, 4.75, 12.5, 16, 22.6, 32, 45, 64, and 90 mm). In addition, the $D_{50}$ and $D_{84}$ (representing grain size diameter of the 50th and 84th percentile of substrate) were computed (Ward et al., 2011); $D_{50}$ and $D_{84}$ were also computed for the reach sub-samples. Channel metrics which characterize thresholds of sediment mobility and channel stability often use $D_{84}$ as representative of
coarser grain size (Olsen et al., 1997). In addition to $D_{50}$ and $D_{84}$ values, $D_{35}$, $D_{65}$, $D_{90}$, and $D_{95}$ were also computed, but only $D_{50}$ and $D_{84}$ are reported. There were also a substantial amount of fine material less than 2 mm in the samples (20-40%); therefore, representative grain sizes less than the 50th percentile could not be consistently computed for all samples. Furthermore, the scope of this project does not seek to characterize grain sizes less than 2 mm. Some reach samples were dominated by fines and the $D_{50}$ would be less than 2.0 mm; in these instances, for graphing and analysis purposes, a value of 1.0 was used as a numerical representation of “less than 2 mm”. Error bars were calculated according to measurement error estimations of bulk sediment sampling (Ferguson and Paola, 1997; Kibler et al., 2011).

2.3.2.3 Riffles

Cross-section and longitudinal profile elevations were graphically evaluated. In addition, changes in the total slope, local slope, and variation of local slope were evaluated within the longitudinal profiles. Total slope was calculated as the difference in elevation and distance between the upstream and downstream most survey points in the riffle survey. Local slope for each profile was computed as the mean of slopes between each adjacent survey point in the profile; the standard deviation of the local slope is a metric of profile slope variability.
2.4 Results

2.4.1 Hydrology

Streamflow conditions during the study period were characterized by an overall larger mean annual discharges in the Olentangy and Scioto Rivers, with smaller peak flows on the Olentangy River and larger peak flows on the Scioto River. Peak flows on the Olentangy River at Worthington (USGS 03226800) were recorded at 164, 189, and 140 m$^3$/s during the water years (October 1 through September 30) 2013 through 2015, respectively, of three-year study period (Figure 2.8) and did not exceed the estimated 2-year peak flow of 259 m$^3$/s (USGS, 2016). Mean annual discharge for the Olentangy River at Worthington is 14 m$^3$/s; mean annual discharge was 23, 22, and 16 m$^3$/s for water years 2013 through 2015, respectively. Peak flows on the Scioto River in Columbus (USGS 03227500) were recorded at 1,025 and 629 m$^3$/s during the water years (2014 through 2015), respectively, of the two-year study period (Figure 2.9); these annual peak flows exceeded the estimated 2-year peak flow of 627 m$^3$/s (USGS, 2016). Mean annual discharge for the Scioto River in Columbus is 43 m$^3$/s; mean annual discharge was 64 and 59 m$^3$/s for water years 2014 through 2015, respectively.

During the study period, both rivers experienced periods of high or low monthly streamflow conditions in comparison to the 30-year norm flows. On the Olentangy River, each summer period experienced months of higher than normal monthly streamflows, especially in July 2013 and June 2015 when the monthly mean was approximately 60 and 30 m$^3$/s, respectively, greater than the monthly norm. Winter months had some variation from the norm, with high streamflows in December 2013 and sustained low streamflows.
in November 2014 thru February 2015 (Figure 2.10). On the Scioto River, similar trends were noted; both summer periods had months of higher than normal monthly streamflows, especially in June 2015 when the monthly mean was approximately 120 m$^3$/s greater than the monthly norm. Winter months had variation from the norm, with high streamflows in December 2013 and sustained low streamflows in November 2014 thru February 2015 (Figure 2.11).
Figure 2.9 Mean daily discharge on the Scioto R. of the two water years (October 2013 thru September 2015) encompassing the study period. The Main Street dam was removed in November 2013. Discharges for the entire study period were available from USGS gage 03227500 located approximately 6 rkm downstream of the removed Main Street dam. Vertical dashed lines indicate the month of a sampling period for sediment and ADCP surveys.
Figure 2.10 Comparison of monthly mean daily discharge on the Olentangy R. of the three water years (October 2012 thru September 2015; solid line) encompassing the study period with the 30 year norm discharge (dotted line). The 30 year norm record is the calculated mean of monthly mean daily discharge from 1981-2010. The 5th Avenue dam was removed in August 2012. Discharges for the entire study period were available from USGS Worthington gage 03226800 located approximately 15 rkm upstream of the removed 5th Avenue dam. Vertical dashed lines indicate the month of a sampling period for sediment and ADCP surveys.

Figure 2.11 Comparison of monthly mean daily discharge on the Scioto R. of the two water years (October 2013 thru September 2015; solid line) encompassing the study period with the 30 year norm discharge (dotted line). The 30 year norm record is the calculated mean of monthly mean daily discharge from 1981-2010. The Main Street dam was removed in November 2013. Discharges for the entire study period were available from USGS gage 03227500 located approximately 6 rkm downstream of the removed Main Street dam. Vertical dashed lines indicate the month of a sampling period for sediment and ADCP surveys.
2.4.2 Geomorphic Change in River Bed Topography

2.4.2.1 Reach-scale erosion and depositional patterns

The DEM of differences (DoDs) indicated changes in elevation within the overlapping portion of two survey periods of the reach as a result of sediment transport patterns. Total erosion, deposition, and net change for all study reaches between individual time periods are summarized in the downstream direction in Table 2.6. OR1, OR2, and SR3 experienced sequences of net deposition and erosion with very limited (e.g., less than 100 m$^3$) net change overall (Table 2.6). OR3, OR4, and SR1 experienced net erosion, with OR3 and SR1 exporting approximately 4530 and 6500 m$^3$, respectively, which is the equivalent of approximately 60 and 20 cm, respectively, of sediment removal over these reaches (Table 2.6). SR1 experienced substantial deposition as well between the first two survey periods that bracketed Autumn 2014 and Winter 2015, followed by net erosion of approximately one quarter of this material (Table 2.6).

For brevity, DEMs, DoDs, and histograms of the DoD elevation change are compiled in Appendix A for all study reaches with the exception of OR4, which is included below to highlight the particular geomorphic changes observed downstream of a removed dam. DoDs demonstrated clear spatial patterns of deposition and erosion for each survey period (Figure A.1, A.3, A.5, A.7, A.9, and A.11). Survey periods indicated an overwhelming dominance of either erosion or deposition for each reach (Figure A.2, A.4, A.6, and A.10) with the exception of OR4 (downstream of a removed dam) and SR3 (downstream of an existing dam) and to a limited extent SR1 (upstream of a
removed dam), which experienced concurrent erosion and deposition over the same individual time interval (Figure 2.13, A.8, and A.11).
Table 2.6 Stream-bed net volumetric change, total erosion volume, and total deposition volume within the reach between sample periods. Negative net change indicates more sediment was eroded from the reach; positive net change indicates more sediment was deposited in the reach. The “overall” time period is DoD between the first and last survey period.

<table>
<thead>
<tr>
<th>River</th>
<th>Reach</th>
<th>Time Period</th>
<th>Net Change (m$^3$)</th>
<th>Erosion (m$^3$)</th>
<th>Deposition (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OR1</td>
<td>Jun 2013-Sep 2013</td>
<td>-367.8</td>
<td>-408.5</td>
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<tr>
<td></td>
<td>Sep 2013-Apr 2014</td>
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<td>4583.6</td>
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<td></td>
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<td>-615.9</td>
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<tr>
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<td>-1672.5</td>
<td>5.1</td>
<td></td>
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<tr>
<td></td>
<td>Sep 2014-Jun 2015</td>
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<td>-6.8</td>
<td>999.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jun 2015-Aug 2015</td>
<td>-550.0</td>
<td>-695.0</td>
<td>145.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall</td>
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<td>-188.0</td>
<td>261.3</td>
<td></td>
</tr>
<tr>
<td>OR2</td>
<td>Jun 2013-Sep 2013</td>
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<td>-596.5</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Sep 2013-Apr 2014</td>
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<td>987.7</td>
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<td></td>
</tr>
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<tr>
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<tr>
<td></td>
<td>Overall</td>
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<td>-109.4</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>OR3</td>
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</tr>
<tr>
<td></td>
<td>Sep 2013-Jun 2014</td>
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<td>Jun 2014-Sep 2014</td>
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<tr>
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<td>Jun 2015-Aug 2015</td>
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<tr>
<td></td>
<td>Overall</td>
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<td>OR4</td>
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<tr>
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<tr>
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<tr>
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<td>-764.7</td>
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<tr>
<td></td>
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<td>38.7</td>
<td>-138.1</td>
<td>176.7</td>
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<tr>
<td></td>
<td>Overall</td>
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<td>-864.7</td>
<td>49.7</td>
<td></td>
</tr>
<tr>
<td>SR1</td>
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<td>-2692.3</td>
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<tr>
<td></td>
<td>Jun 2015-Aug 2015</td>
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<td>-6085.9</td>
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</tr>
<tr>
<td></td>
<td>Overall</td>
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<td>-7423.3</td>
<td>953.7</td>
<td></td>
</tr>
<tr>
<td>SR2</td>
<td>Sep 2014-Jun 2015</td>
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<td>-805.9</td>
<td>23443.7</td>
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</tr>
<tr>
<td></td>
<td>Jun 2015-Aug 2015</td>
<td>-5971.2</td>
<td>-6010.4</td>
<td>39.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall</td>
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<td>-1245.4</td>
<td>10725.9</td>
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<tr>
<td>SR3</td>
<td>Sep 2014-Jun 2015</td>
<td>380.7</td>
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<td>2146.2</td>
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</tr>
<tr>
<td></td>
<td>Jun 2015-Aug 2015</td>
<td>-382.9</td>
<td>-2067.9</td>
<td>1685.1</td>
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</tr>
<tr>
<td></td>
<td>Overall</td>
<td>-73.1</td>
<td>-1455.2</td>
<td>1382.2</td>
<td></td>
</tr>
</tbody>
</table>
2.4.2.1.1 Olentangy River

Overall, upstream of the existing dam, OR1 experienced a net deposition of sediment for the study period although sequential deposition and erosion were observed during individual survey periods (Table 2.6; Figure A.1). The reach experienced net erosion over the three summer seasons of the study period, and net deposition over the two winter seasons (Figure A.1). The greatest magnitude of change occurred over winter between the September 2013 and April 2014 surveys with approximately 4580 m$^3$ of sediment deposition, almost three times greater than other net erosion or net deposition values computed for this reach (Table 2.6).

The two reaches upstream of the removed dam experienced net erosion, although OR3 experienced substantially more erosion (~4530 m$^3$ vs 94 m$^3$), which is attributed to restoration activities at this site in the active channel. As seen at OR1, OR2 experienced sequential deposition and erosion that corresponded to winter-spring and summer seasons (Table 2.6), respectively and was concentrated along the river left margin of the channel (Figure A.3). Erosion dominated all survey periods in the actively restored upstream reach, OR3, with the exception of the time period between June and September 2014, which essentially showed no change throughout the reach (Figure A.5). The final two survey periods that extend from Sep 2014 to Aug 2015 were characterized by erosion that occurred throughout most of the study reach (Figure A.5).

Downstream of the dam removal, OR4 had an overall net erosion of approximately 815 m$^3$ (Table 2.6). However erosion and deposition were concurrent throughout the reach between each survey (Figure 2.12), creating a bimodal distribution
of elevation change centered over 0 m (Figure 2.13). Net erosion occurred over the first year, followed by net deposition during the summer and net erosion during the winter over the last year and a half of the study period, which is the opposite of the seasonal trends observed at OR2 and OR1, where winters were net depositional and summers were net erosional.

2.4.2.1.2 Scioto River

Upstream of the removed dam, SR1 had net erosion between each survey (Figure 2.6), although some concurrent deposition occurred during the winter-spring between September 2014 and June 2015 (Figure A.7). Downstream of the removed dam, SR2 experienced substantial deposition during winter-spring 2014 (~22640 m³; Figure 2.6), which is the equivalent of 50 cm of deposition throughout the reach, but was concentrated along the river right margin of the reach (Figure A.9). Processes within the reach were dominated by engineering activity through the construction of a large sediment bar and holding area on the river right banks for construction equipment, which resulted in the high amounts of deposition within the reach that cannot be attributed to fluvial processes. This was engineered deposition which obscures the presence of any seasonal deposition or trends over winter. Net erosion measured in the subsequent survey, which captured the summer 2015 period, removed approximately one quarter of newly deposited material (Table 2.6, Figure A.9). Similar to OR4, downstream of an existing dam, SR3, had concurrent deposition and erosion throughout the reach (Figure A.11), although overall net erosion and net deposition patterns followed the seasonal sequence of summer and winter, respectively as was observed in OR1 and OR2 (Figure 2.6).
Figure 2.12 DEMs (top row) and DoDs (bottom row) for OR4, downstream of dam removal. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction. The empty portion is where a bridge crosses the reach. Note that the first time period (June 2013) does not extend upstream enough to include the deep pool visible in the subsequent surveys.
Figure 2.13 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven OR4 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicated deposition.
2.4.2.2 Qualitative assessment of reach macrofeatures

Geomorphic changes of the reach macrofeatures that include pools, runs, and riffles occurred throughout the study period interpreted based on DEMs and DoDs for each study reach. Observed changes in macrofeatures generally corresponded to anticipated change based on the treatment of the reach (control or experimental) and location relative to an existing or removed dam (upstream or downstream).

2.4.2.2.1 Olentangy River

Upstream of the existing dam (OR1) had little change in channel morphology, with intermittent scour and fill at the middle and upstream portions of the reach (Figure A.1). Deposition and sediment bar growth in the downstream portion of the reach immediately upstream of the existing dam were visually observed but not quantified. The reach was generally deep (> 2 m during baseflow conditions) throughout with a large, vegetated exposed gravel bar on river left of the downstream portion of the reach.

OR2, the passively-restored reach located upstream of the removed dam, was characterized by a general, relatively non-distinct, pool-run sequence with an exposed gravel bar located on river left in the downstream portion that existed prior to the start of the study. Macrofeatures throughout this reach, which included runs and shallow pools, remained relatively stable despite the sequential erosion and deposition that had occurred in this reach (Figure A.3).

OR3, the actively-restored reach upstream of the dam removal, exhibited the most change. The DEM of the first survey in June 2013 displayed few distinct features and no distinct thalweg. This survey occurred during very low streamflow conditions during
which much of the channel was exposed resulting in a narrow wetted channel area (~20 m vs mean channel widths of 42 m during subsequent survey periods). Active restoration, which occurred from approximately August 2013 and extended to late winter 2014, re-graded the channel constructing a distinct pool-run sequence. The four subsequent surveys following active channel restoration activities indicated that pools and runs remained relatively stable with pools continuing to deepen and length (Figure A.5).

OR4, located downstream of the removed dam, was characterized by a bend in the upstream portion of the reach leading into a straight channel in the middle and downstream portion of the reach (Figure 2.12). The large pool in the upstream portion was approximately 4 m deep and experienced minor changes in shape over time, but included widening (~5 m) of the upstream portion between September 2014 and June 2015. Overall, the small pool upstream of the bridge lengthened and had re-established since September 2013 survey where it had accumulated sediment; the small pool below bridge was relatively stable with some minor changes in shape between sampling. The channel below the island was a stable run leading to pool, which was cut off by most surveys.

2.4.2.2 Sciot River

Upstream of removed dam, SR1, was characterized by small pools associated with bridge pillars that lead into a wide, low-gradient run. Bank reconstruction between the first two surveys widened the channel above the mid-reach bridge and a pool was established on river left (Figure A.7). The large, deep pool below the bridge widened and lengthened (~20 m) to a rectangular shape by August 2015; the deepest portion of the
pool had elongated by approximately 10 m. The September 2014 survey had been truncated by a downstream riffle (possibly used for construction equipment), but this riffle was gone by the June 2015 survey. The downstream portion of the reach was a simple run which experienced little change between the last two surveys.

In the SR2 reach, which was downstream of the dam removal, a large bar was constructed between the September 2014 survey and June 2015 as part of the dam removal activities to serve as a holding area for equipment and remained for the duration of the study period. The thalweg shifted to river left between the first two survey periods and remained at this location at the August 2015. As a result, the pool at this location deepened and continued to deepen throughout study period. However the reach remained dominated by the engineered deposition observed during the June 2015 survey (Figure A.9).

SR3, downstream of an existing dam, was characterized by a large gravel bar at the upstream portion of the reach that directed most of the flow along river right during normal flow conditions (Figure A.11). Concurrent deposition and erosion observed in the DoDs translated to relative stability of existing channel features in this reach, which included maintenance of a large pool in the downstream region of the reach on river left and several smaller, shallow pools throughout the reach.
2.4.2.3 Metrics of topographic complexity

Differences in topographic complexity metrics were statistically evaluated through time and across study sites using univariate and multivariate approaches. The variance for each metric and correlation among metrics were assessed to determine if the datasets met criteria for statistical comparisons. We first assessed the distribution for each metric (standard deviation of elevation, mean rugosity standard deviation of curvature, and elevation range) and scale (0, 5, 10, and 20 m) calculated within each reach and time period (Figure 2.14; Figure 2.15). Range was strongly correlated with standard deviation of elevation (mean Spearman’s \( \rho = 0.93 \ (\pm 0.09) \)) and therefore was not included in further analysis. Standard deviation of elevation was also correlated with mean rugosity (mean Spearman’s \( \rho = 0.89 \ (\pm 0.05) \)), but both metrics were included because of the unique spatial characteristics they demonstrate. In particular, the standard deviation of elevation captures the variability of elevation, where mean rugosity also simultaneously captures elements of the range metric, which was excluded.

2.4.2.3.1 Univariate Comparison

The boxplots display a consistent increase in magnitude of values for each metric with increasing spatial scale for all metrics, which suggests that the behavior of each metric was consistent across scales allowing us to constrain our analysis to an individual spatial scale (Figure 2.14; Figure 2.15). Therefore, for the univariate analysis, the within-reach metric trends were evaluated at the 5-m scale to capture the fine-scale heterogeneity. At the 5-m scale, each repeat, fixed point describes the river bed surface within a 5-m radius (approximately 81 grid cells and 80 m\(^2\)). We compared repeat, fixed
locations that were shared between individual surveys. Individual survey extents did not overlap all point locations, which resulted in the exclusion of some fixed locations in the pairwise comparison. Fixed points and overlay of paired survey extents are displayed in Appendix B for the Olenetangy River reaches; analysis of Scioto River reaches used repeat points which were shared between the three surveys. Non-overlapping regions tended to occur along channel margins, where bed elevation change is limited, and in some cases along upstream and downstream extents of a survey. In general, shared points represent on average 75% (±17%; Table B.1) of the overall points in an individual survey, which captured the main portions of the channel that had the greatest potential for change and were therefore representative of the reach.

There were some noticeable differences in reach-scale heterogeneity metrics between study sites and how these metrics changed through time. In general, as seen in the boxplots, OR2 and OR3 had smaller values and associated variability for standard deviation of elevation, mean rugosity, and standard deviation of curvature relative to OR1 and OR4 (Figure 2.14). On the Scioto River, the reaches had similar topographic complexity, though SR1 had greater variability in mean rugosity and standard deviation of elevation (Figure 2.15).

Over time, elevation standard deviation and curvature standard deviation significantly changed at four of the seven reaches, and mean rugosity significantly changed at one of the seven reaches (Table 2.7). Elevation standard deviation significantly increased over time at OR1, OR3, and OR4, and significantly decreased over time at SR3. Curvature standard deviation significantly increased over time at OR1
and SR2, and significantly decreased over time at OR3 and OR4. Mean rugosity significantly decreased at SR3. Significant changes in topographic heterogeneity were not observed at OR2 nor SR1.

Figure 2.14 Distribution of metric values within Olentangy R. reaches at all timer periods. Each time period had four boxplots displaying the distributions at scales 5, 10, 20, and 50-m. Survey periods are June 2013, September 2013, April 2014, June 2014, September 2014, June 2015, and August 2015. Survey time period 6 is missing as it corresponds to the incomplete December 2014 surveys.
Figure 2.15 Distribution of metric values within Scioto R. reaches at all timer periods. Each time period had four boxplots displaying the distributions at scales 5, 10, 20, and 50-m. Survey periods September 2014, June 2015, and August 2015. Survey time period 6 is missing as it corresponds to the incomplete December 2014 surveys.
Table 2.7 Results of linear mixed models for each reach and topographic heterogeneity metric on log transformed scale. The coefficient estimate for the fixed effect (time) are reported with standard error and p-values. Outputs in red indicate significant change over time.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Elevation Stdev.</th>
<th>Mean Rugosity</th>
<th>Curvature Stdev.</th>
</tr>
</thead>
<tbody>
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<td>OR1</td>
<td>0.004</td>
<td>0.002</td>
<td>0.016</td>
</tr>
<tr>
<td>OR2</td>
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<td>0.122</td>
</tr>
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<td>OR3</td>
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<td>&lt; 0.001</td>
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<td>OR4</td>
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<td>0.028</td>
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<td>0.006</td>
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<tr>
<td>SR3</td>
<td>-0.014</td>
<td>0.005</td>
<td>0.005</td>
</tr>
</tbody>
</table>

85
2.4.2.3.2 Multivariate comparison

Reach-scale topographic metrics were also compared using multivariate NMDS and include rugosity, skewness and kurtosis of elevation, standard deviation of elevation, and standard deviation of curvature. A Spearman’s correlation matrix of the five metrics revealed high correlation between skewness and kurtosis ($\rho = -0.79$) and rugosity and curvature standard deviation ($\rho = 0.85$); therefore, skewness and curvature standard deviation were not used in NMDS analysis. NMDS was performed on 1) Olentangy River reaches alone and 2) Olentangy and Scioto River reaches combined. The Scioto River was combined with the Olentangy River study sites because of the limited sample number ($n = 9$), which prevented model convergence in the NMDS analysis. The three reach-scale metrics (rugosity, kurtosis, and elevation standard deviation) were statistically significant for each NMDS ordination (Table 2.8).

The NMDS ordination plots of mean-centered reach-scale metrics indicated few distinct patterns. Surveys within the same reach were not more similar than surveys over the same time period but across different reaches (Figure 2.16). PerMANOVA results indicated no significant differences between groupings based on time period ($p = 0.888, F$-statistic = 0.51). The NMDS1 axis was dominated by kurtosis and NMDS2 axis was dominated by rugosity and elevation standard deviation (Table 2.8). PerMANOVA results indicated that the multivariate reach-scale topographic metrics are not significantly different for the Olentangy River reach groupings ($p = 1.000, F$-statistic $< 0.001$). The first survey of OR3 (t1; June 2013) plotted higher along the NMDS1 axis, distinctly different from the grouping of other points. The addition of the three Scioto
River reaches did not contribute to any distinct patterns between reaches or time periods (Figure 2.17).

Changes in geomorphic heterogeneity over time were statistically significant within an individual reach, as shown by the univariate analysis; these changes were small enough on a larger scale (when comparing to other reaches) that the changes within a reach were not noticeable and reaches were not significantly different from each other, as indicated by the multivariate analyses.

Table 2.8 Pearson correlation coefficients for NMDS ordinations among reach-scale geomorphic metrics and squared correlation coefficient ($R^2$) between metrics and ordination scores; significance of correlation were evaluated with 999 permutation tests.

<table>
<thead>
<tr>
<th>Reach-Scale Metric</th>
<th>Olentangy R.</th>
<th>Olentangy and Scioto R.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMDS1</td>
<td>NMDS2</td>
</tr>
<tr>
<td>Rugosity</td>
<td>-0.008</td>
<td>0.999</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0.999</td>
<td>0.020</td>
</tr>
<tr>
<td>Elevation Standard Deviation</td>
<td>-0.020</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Statistical significance codes: ** $p < 0.001$, * $p < 0.05$
Figure 2.16 Nonmetric multidimensional scaling (NMDS) ordination plot for Olentangy River reaches at all time periods for reach-scale metrics rugosity, kurtosis, and elevation standard deviation. Time periods are labeled for each point (t1: Jun 2013, t2: Sep 2013, t3: Apr 2014, t4: Jun 2014, t5: Sep 2014, t7: Jun 2015, and t8: Aug 2015). NMDS1 is dominated by kurtosis, increasing from left to right. NMDS2 is dominated by rugosity and elevation standard deviation, increasing from top to bottom. Stress was reported near 0. Square points represent control reaches. Circle points represent reaches upstream of removed dam. Triangle points represent reaches downstream of removed dam.
Figure 2.17 Nonmetric multidimensional scaling (NMDS) ordination plot for Olentangy and Scioto River reaches at all time periods for reach-scale metrics rugosity, kurtosis, and elevation standard deviation. Time periods are labeled for each point (t1: Jun 2013, t2: Sep 2013, t3: Apr 2014, t4: Jun 2014, t5: Sep 2014, t7: Jun 2015, and t8: Aug 2015). NMDS1 is dominated by kurtosis, increasing from right to left. NMDS2 is dominated by rugosity and elevation standard deviation, increasing from top to bottom. Stress was reported near 0. Square points represent control reaches. Square points represent control reaches. Circle points represent reaches upstream of removed dam. Triangle points represent reaches downstream of removed dam.
2.4.3 Sediment

Changes in sediment grain size were observed over the three year and two year study periods and are reach specific. Reach-scale changes are described as the culmination of the three sub-samples at upstream, middle, and downstream area of the reach.

2.4.3.1 Olentangy River

Upstream of the existing dam, OR1 experienced little change in grain size distributions. Upstream of the removed dam, reaches OR2 and OR3 both experienced sequences of significant coarsening and fining. Downstream of the removed dam, OR4 experienced overall coarsening through time. Changes in grain size were more noticeable for $D_{84}$ relative to the $D_{50}$. Summarized trends for $D_{50}$ and $D_{84}$ at each reach over time (Figure 2.18, Table 2.9) were consistent with trends seen in the plots of cumulative percent finer for each reach (Figure 2.19).

The upstream control reach underwent little change in sediment grain size distributions. OR1 was dominated by fines (< 2 mm) on river right while the downstream portion of the reach on river left had a gravel bar, which was not sampled until September 2014. The change in sampling location accounted for the sudden coarsening of reach-scale $D_{84}$; no other reaches demonstrate grain size diameter of one sub-sample being such a driver of reach-scale metrics (Figure 2.20). $D_{84}$ experienced some further coarsening since the change of sample location, which coarsened from 22 mm in September 2014 to 31 mm in August 2015. Field observations indicated that the gravel bar is increasing in size and retaining more coarse, gravelly sediment on the upstream side.
The $D_{50}$ of passively-restored, upstream experimental reach, OR2, remained gravel-sized throughout, initially coarsening from 18 to 26 mm over the course of a year. The $D_{50}$ was significantly variable over the final four sample periods, and had fined to 8.4 mm by the final sample period. Statistically noticeable changes in $D_{84}$ also occurred between the latter four sample periods, which sequentially fined and coarsened as well. Overall, the reach grain size had little net change. The actively-restored, upstream experimental reach, OR3, coarsened between June 2013 and April 2014; $D_{84}$ increased from 2.9 to 36 mm and $D_{50}$ coarsened from fine, sandy sediment $<2$ mm to 5.3 mm fine gravel. The active restoration took place in this reach from approximately Autumn 2013 thru Winter 2014. Initial coarsening was followed by a sequential fining and coarsening; $D_{84}$ decreased to 13 mm in September 2014. Overall, the reach coarsened over time and the $D_{84}$ had coarsened to 25 mm by August 2015.

The initial fining in the downstream experimental reach, OR4, was significant in the $D_{84}$, decreasing by 10 mm over the course of a year. During this time, the $D_{50}$ did not change significantly, remaining classified as mostly sand ($<2$ mm) or very fine gravel (2.2 mm). The initial fining was followed by an artificial coarsening in September 2014. The grain size distributions fined and then coarsened between the last three sample periods; $D_{50}$ fined from medium-sized gravel (8.8 mm) to sand, then coarsened to medium-sized gravel (13 mm). $D_{84}$ fined from very coarse gravel (44 mm) to coarse gravel (23 mm), and then coarsened back to very coarse gravel (51 mm). Overall, the reach grain size increased over time. Increases in grain size diameter for $D_{50}$ and $D_{84}$ in the second half of the study period are attributed to changes in field sampling location.
Prior to September 2014, sampling had been conducted on the right bank of the study reach but was changed to sampling on river left.

Figure 2.18 Changes in reach-scale grain size distribution over time on the Olentangy River. The sediment sample periods are June 2013, September 2013 (missing for OR3), April 2014, September 2014, June 2015, and August 2015. Horizontal dotted lines represent grain size upper limits of sand, fine gravel, medium to coarse gravel, and very coarse gravel.
Figure 2.19 Reach-scale cumulative percent finer on the Olentangy River over time. Point type for lines are an indication of season, squares are spring or early summer and X’s are autumn. Vertical dotted lines are at 2 mm and 64 mm, which is the size range for gravel. Less than 2 mm is sand and greater than 64 mm is cobble.

Table 2.9 Summary table of reach-scale $D_{50}$ and $D_{84}$ values (mm), listed respectively, on the Olentangy and Scioto Rivers over time. An asterisk (*) indicates a significant change in grain size from the previous sample periods.

<table>
<thead>
<tr>
<th>Sample Period</th>
<th>OR1</th>
<th>OR2</th>
<th>OR3</th>
<th>OR4</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun 2013</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>18</td>
<td>50</td>
<td>&lt; 2</td>
<td>2.9</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Sep 2013</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>22*</td>
<td>51</td>
<td>2.2</td>
<td>14*</td>
<td></td>
</tr>
<tr>
<td>Apr 2014</td>
<td>&lt; 2</td>
<td>&lt; 2</td>
<td>26*</td>
<td>53</td>
<td>5.3*</td>
<td>36*</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Sep 2014</td>
<td>2.4</td>
<td>22</td>
<td>9.4*</td>
<td>42*</td>
<td>2.1*</td>
<td>13*</td>
<td>8.8</td>
</tr>
<tr>
<td>Jun 2015</td>
<td>&lt; 2</td>
<td>28*</td>
<td>15*</td>
<td>53*</td>
<td>5.9*</td>
<td>36*</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Aug 2015</td>
<td>&lt; 2</td>
<td>31</td>
<td>8.4*</td>
<td>42*</td>
<td>3.9</td>
<td>25*</td>
<td>13*</td>
</tr>
</tbody>
</table>

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Figure 2.20 Comparison of OR1 upstream control and OR2 experimental upstream sub-reach samples and reach-scale $D_{50}$ and $D_{84}$. The sudden coarsening of reach-scale $D_{84}$ at OR1 in Sept 2014 was due to the change in sampling location of the downstream sub-sample. This is compared with OR2 where no one sub-sample is the main driver of reach-scale $D_{50}$ or $D_{84}$. The sediment sample periods are June 2013, September 2013, April 2014, September 2014, June 2015, and August 2015.
2.4.3.2 Scioto River

Upstream of the removed dam, SR1 experienced overall coarsening of sediment. Downstream of the removed dam, SR2 experienced fining and coarsening between sample periods. The downstream control reach, SR3, experienced some fining. Changes in grain size are more noticeable for $D_{84}$ relative to the $D_{50}$. Summarized trends for $D_{50}$ and $D_{84}$ at each reach over time (Figure 2.21; Table 2.9) are consistent with trends seen in the plots of cumulative percent finer for each reach (Figure 2.22).

The restored, upstream experimental reach, SR1, experienced overall coarsening of $D_{84}$ from 27 mm coarse gravel to 44 mm very coarse gravel. Coarsening was less noticeable for $D_{50}$, but significantly coarsened from fine gravel to medium-sized gravel between the final two sample periods over Summer 2015. Within the downstream experimental reach, SR2, the upstream and mid-reach river banks are heavily reinforced with large cobble and boulders with very fine sand and organic material in between (Figure 2.23). The cobble and boulders were too large to be collected with the McNeil sampler. SR2 was dominated by fines and there was no significant change in the $D_{50}$, while the $D_{84}$ coarsened by 15 mm from fine gravel to coarse gravel between the final sampler periods of June and August 2015. The downstream control reach, SR3, experienced an overall fining of $D_{50}$ and $D_{84}$. The change is significant between the first two sample periods, while change in the grain size between the final two sample periods was not significant.
Figure 2.21 Changes in reach-scale grain size distribution over time on the Scioto River. The sediment sample periods are September 2014, June 2015, and August 2015. Horizontal dotted lines represent grain size upper limits of sand, fine gravel, medium to coarse gravel, and very coarse gravel.
Figure 2.22 Reach-scale cumulative percent finer on the Scioto River over time. Point type for lines are an indication of season, squares are spring or early summer and X’s are autumn. Vertical dotted lines are at 2 mm and 64 mm, which is the size range for gravel. Less than 2 mm is sand and greater than 64 mm is cobble.

Figure 2.23 Bank substrate at SR2, downstream of dam removal. Heavily reinforced banks with large cobble and boulders with very fine sediment and organic material.
2.4.4 Riffles

There does not appear to be any observable trend in progressive riffle downstream steepening in OR3 and OR4, with the exception of the river right portion of OR3 riffle, which steepened from -0.005 to -0.011 m/m (Figure 2.24). Deposition within the riffle was also observed within the longitudinal profiles (Figure 2.25) and cross-sections (Figure 2.26) at OR3 between the 2014 and 2015 sample periods, but this was not evident in the OR4 longitudinal profiles or cross-sections. Cross-sectional shape did not change over time for any of the riffles (Figure 2.26).

![Diagram showing reach slope of Olentangy River riffles at OR3 and OR4. Reach slope for each profile was calculated as the slope between upstream and downstream most point.](image-url)
Figure 2.25 Longitudinal profiles of middle portion of riffle at Olentangy reach 3. The profile from May 2015 is excluded because it was located approximately 5 m to river left. Distance is increasing in the downstream direction.

Figure 2.26 Cross-section profiles of upstream portion of riffle at OR3. Distance increases from river left to river right.
2.5 Discussion

Following the removals of a lowhead dam on the Olentangy and Scioto Rivers, I hypothesized that river reaches upstream of the removed dam would demonstrate an overall increase in topographic heterogeneity and coarsening of substrate as a result of erosion into impounded sediments. Our results support this hypothesis, as upstream reaches experienced more frequent erosion between survey periods and overall net erosion with overall coarsening of sediment (Table 2.10). Changes in topographic heterogeneity occurred only at one of the three upstream reaches. The upstream reaches were also geomorphically influenced by the seasonal hydrological regime, which we did not take into account in our hypotheses; we observed that seasonality corresponds to the sequential pattern of deposition and erosion and substrate coarsening and fining.

Downstream of removed dams, I expected the reaches to experience sediment coarsen and increase in heterogeneity in riverbed topography as patches of recently deposited sediment were eroded and transported downstream. Our results partially support this hypothesis. Because of the engineered deposition at SR2, it is difficult to see what fluvial processes were actually occurring over winter and we were unable to surmise winter trends at this reach. There was summer erosion with sediment coarsening between the final two surveys (Table 2.10), which is different from the summer deposition with sediment coarsening observed at OR4 during the same time period. Erosion and deposition were concurrent within OR4 between each survey period, with net erosion occurring between the first four surveys and substrate initially fining (Table 2.10). Sequential coarsening and fining occurred over the last three surveys and was
likely a result of seasonal changes in the flow. Elevation standard deviation significant increased over time at OR4, but curvature standard deviation significantly decreased as well.

Table 2.10 Generalized summary of changes in elevation, macrofeatures, substrate, and topographic heterogeneity within the seven study reaches.

<table>
<thead>
<tr>
<th>River</th>
<th>Study Reach</th>
<th>Reach Conditions</th>
<th>Change in Elevation</th>
<th>Change in Macrofeatures</th>
<th>Change in Substrate</th>
<th>Change in Heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olentangy</td>
<td>OR1</td>
<td>upstream of existing dam</td>
<td>net deposition; seasonal sequence</td>
<td>mild, stable</td>
<td>little change</td>
<td>significant increases</td>
</tr>
<tr>
<td></td>
<td>OR2</td>
<td>upstream of removed dam; passive restoration</td>
<td>net erosion; seasonal sequence</td>
<td>mild, stable</td>
<td>no net change; seasonal sequence</td>
<td>no change</td>
</tr>
<tr>
<td></td>
<td>OR3</td>
<td>upstream of removed dam; active restoration</td>
<td>net erosion; erosion more common</td>
<td>construction of pool-run sequence</td>
<td>coarsening; seasonal sequence</td>
<td>significant changes</td>
</tr>
<tr>
<td></td>
<td>OR4</td>
<td>downstream of removed dam</td>
<td>net erosion; concurrent</td>
<td>moderate; pool adjustments</td>
<td>initial fining; overall coarsening</td>
<td>significant changes</td>
</tr>
<tr>
<td>Sciooto</td>
<td>SR1</td>
<td>upstream of removed dam; restoration</td>
<td>net erosion; erosion more common</td>
<td>moderate; pool enlargement</td>
<td>some coarsening</td>
<td>no change</td>
</tr>
<tr>
<td></td>
<td>SR2</td>
<td>downstream of removed dam</td>
<td>engineered deposition</td>
<td>moderate; thalweg adjustment</td>
<td>coarsening; seasonal sequence</td>
<td>some significant change</td>
</tr>
<tr>
<td></td>
<td>SR3</td>
<td>downstream of existing dam</td>
<td>net erosion; concurrent</td>
<td>mild, stable</td>
<td>some fining</td>
<td>significant decreases</td>
</tr>
</tbody>
</table>

2.5.1 Seasonal Trends in Geomorphic Change

Throughout the study period on the Olentangy and Scioto Rivers, our results indicated over-arching seasonal trends within the reaches linked with the seasonal
hydrology as we moved further away from the dam removals, specifically within the control reaches (OR1 and SR3) and OR2, which was located further upstream of the dam removal and was not actively restored. At these reaches, the most prominent seasonal trends were observed with the net erosion or deposition within a reach between surveys; winter corresponded with net deposition, while summer corresponded with net erosion. Seasonal trends at these reaches were not as apparent for change in sediment. Erosion and deposition often coincided with either substrate coarsening or fining, but was not consistent between reaches.

2.5.2 Upstream Responses to Dam Removal

All three reaches upstream of removed dams were net erosional over the duration of the study period, which suggests that sediments within the former dam impoundments had been mobilized and transported downstream. Reach sediment also coarsened between the first three surveys on the Olentangy and Scioto Rivers. The coarsening is consistent with other research findings that after dam removal, the former impoundment initially erodes and exports finer sediment, which reveals underlying coarser sediment (Bushaw-Newton et al., 2003; Doyle et al., 2003a; Pearson et al., 2011). After the removal of the 2.0-m Manatawny Creek dam (Pennsylvania), the impoundment had eroded 0.5 m of fine sediment and exposed coarser sediment (Bushaw-Newton et al., 2003). Within-season geomorphic changes indicated summer flows corresponded to net erosion, coarsening of sediment at SR1, and fining of sediment at OR2 and OR3, Winter flows corresponded to net deposition at OR2 and coarsening of sediment at OR2 and OR3.
The actively restored OR3 responded differently from the other upstream reaches because erosion was typically the dominant process between survey periods, regardless of season. The initial differentiation of OR3 was also apparent in the NMDS analysis between the first two surveys; the June 2013 survey (t1) of OR3 plotted differently from the other OR3 time periods (and other reaches as well), but subsequently became more similar to the other grouping of points. OR3 also was the only upstream reach to experience overall significant change in topographic heterogeneity; the elevation standard deviation significantly increased while curvature standard deviation significantly decreased over time. This may be a consequence of active channel restoration within the reach, unlike OR2 and SR1 which did not have the same extent of in-channel restoration completed in OR3. The decrease in curvature standard deviation may be a result of how the channel was shaped during active restoration. The lack of overall geomorphic changes (topographic heterogeneity and sediment) and seasonal winter deposition and summer erosion patterns at OR2 indicate that the reach might not have been as geomorphically influenced by the lowhead dam.

OR2 and OR3 had lower values for topographic heterogeneity and less variability in comparison to OR1 and OR4; this is consistent with DEM observations. OR1 and OR4 are more geomorphically complex with large sediment bars and deeper pools in comparison with OR2 and OR3 which have gentler sloping runs and smaller, shallow pools.
2.5.3 Downstream Responses to Dam Removal

The overall net change in elevation for the downstream reaches differed between the two rivers. SR2 was dominated by engineered deposition between the first two study periods (over winter). It is difficult to see what fluvial processes were actually occurring over winter and we were unable to surmise winter trends at this reach because of the engineered deposition at SR2. There was summer erosion with sediment coarsening between the final two surveys at SR2, which were different from the summer deposition with sediment coarsening observed at OR4 during the same time period. OR4 experienced net erosion over the study period, which suggests that previously impounded sediment was able to move through the reach. Other dam removal studies suggest that the release of fine sediment from former impoundments will homogenize reach macrofeatures (Pizzuto, 2002), which we expected would occur after dam removal and prior to the start of the study period. The engineered deposition event within SR2 limitedly changed reach heterogeneity and the reach only experienced significant increase in curvature standard deviation over time. The NMDS ordination does display the first time period (t1) of OR4 separated from the grouping of the rest of points, but this is likely due to the DEM of the June 2013 survey not extending upstream enough to include the distinctive deep pool.

Concurrent deposition and erosion between time periods occurred predominantly in OR4 and SR3; this was expected in OR4 as a result of translation and dispersion of recently deposited sediment within the reach (Pizzuto, 2002). Similar variable channel adjustment occurred downstream of the 3.4-m Anaconda dam (Connecticut), where
deposited sediment bars gradually moved further downstream and shrank in size over time (Wildman and MacBroom, 2005). Furthermore, the release of coarser sediment from a dam can cause variable channel adjustments and changes in reach heterogeneity depending on how the sediment moves through the system. Following the removal of the 2.1-m Brownsville dam (Oregon), the reach below the removed dam developed more heterogeneous habitat as a result of the release of coarser sediment within the dam impoundment (Kibler et al., 2011). The concurrent deposition and erosion within OR4, may contribute to the lack of coherency with apparent coarsening and fining patterns of sediment and overall significant increase in elevation standard deviation with significant decrease in curvature standard deviation. This reach also was more geomorphically complex with deeper pools, runs, and sediment bars, which may have contributed to the variable nature of how sediment was eroded and deposited within the reach.

2.5.4 Geomorphic Response within an Urban Setting

This particular study distinctly places the geomorphic responses to lowhead dam removal within the context of an urbanized landscape. Urban streams and rivers constrain river channels and floodplains with limited lateral mobility as a result of development along the river corridor; these conditions were observed along the study reaches. High concentrations of impervious surfaces in urbanized areas alter hydrological and sediment regimes and stream geomorphology as a result of the increase in total amount of runoff and the reduction in the time to peak discharges in the hydrograph (Gurnell et al., 2007; Paul and Meyer, 2001). The flashy peak flows are capable of transporting sediment from upstream sources and depositing the sediment within reaches while simultaneously
transporting sediment out of the reach (Gurnell et al., 2007; Konrad, 2003). Manmade features in the river also contribute to the alteration of sediment movement; bridges footings can cause erosion within the channel (Paul and Meyer, 2001), as seen in within OR4 and SR1 and immediately upstream of SR2.

Channel enlargement either through channel widening or incision is a common consequence of the altered flow regime in urban rivers (Hammer, 1972; Pizzuto et al., 2000). The overall erosion observed at the reaches above dam removal (OR2, OR3, and SR1), below dam removal (OR4), and below an existing dam (SR3) demonstrates the continuation of channel incision as possible result of urbanization and the altered hydrologic flow regime. Our results suggest that the geomorphic response following lowhead dam removal in an urban setting is likely influenced by the seasonality of the hydrologic flow and sediment regimes.
2.6 Conclusions

Following lowhead dam removal, a variety of geomorphic outcomes can occur, typically as a consequence of the catchment- and reach-scale characteristics and the physical character of the removed dam. We anticipated a large amount of erosion and substrate coarsening upstream of the dam removal paired with variable sediment movement out of the downstream reach with increasing time, resulting in sediment coarsening and increases in heterogeneity. Upstream of dam removal, we observed net erosion overall with some seasonally driven deposition, especially within the passively-restored reach. We attribute the large amount of erosion within the actively-restored reach to the in-channel restoration process. The responses downstream of dam removal were more variable. The Olentangy River had concurrent erosion and deposition between surveys with overall net erosion and variable coarsening and fining of channel substrate between surveys. In contrast, the Scioto River experienced engineered deposition and summer erosion with overall net deposition and some coarsening of substrate. Because sediment responses were variable in the downstream reaches, it is difficult to draw trends throughout the downstream reaches. Further research will be needed to confirm how downstream reaches respond following dam removals in urban systems.

Even though there were observed statistically significant differences over time in topographic heterogeneity, these changes may not be significant enough to alter river habitat and influence the ecological structure within the river; in which case, removing a lowhead dam may not have long-term negative impacts on river habitat. These observed
geomorphic responses may give insight into the ecological responses observed at the study reaches, in response to the lowhead dam removals.

The variety of outcomes observed in this study are nonetheless important additions to the growing body of research surrounding dam removal, and this information can provide useful comparisons with other dam removals for potential future dam removal projects. Our study on the Olentangy and Scioto Rivers emphasizes the need for multi-year monitoring of dam removals in different landscapes, particularly urban landscapes, and also accounting for seasonal hydrology.
2.7 Literature Cited


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Chapter 3 – Conclusions

3.1 Summary of the Study Setup

Dams affect over half of the large river systems in the world (Nilsson et al., 2005) and are ubiquitous features on rivers flowing in the United States (Graf, 1999; Stanley and Doyle, 2002). Approximately 2 million small dams (<7.6 m) exist in the United States (Graf, 1993), many of which are considered lowhead or run-of-river structures whereby water flows freely over the crest of the structure (Csiki and Rhoads, 2010). By the year 2020, 80% of the dams in the U.S. that are 1.8 m or higher will have reached at least 50 years of age, and will be considered at the end of their projected design life (Evans et al., 2000). As dams reach the end of their functionality, the practice of their removal rather than repairing or maintaining has become a more common management and restoration practice (Evans et al., 2000; Poff and Hart, 2002). Consequently, there is growing interest in understanding physical channel adjustment once a dam is removed (Stanley and Doyle, 2003).

This study’s goal was to report on geomorphic adjustment of two mid-sized, urban rivers to lowhead dam removal in the two to three years following dam removal. Geomorphologic response was quantified through repeated field measurements of channel bathymetry using an acoustic Doppler current profiler (ADCP) and characterization of riverbed substrate composition through the collection of bedload and
near surface sediment samples. This study utilized a paired control-treatment design to quantify the geomorphic response of stream channel reaches above and below a removed run-of-river, lowhead dam, in comparison with reaches adjacent to existing run-of-river, lowhead dams.

3.2 Major Findings

Throughout the study period on the Olentangy and Scioto Rivers, our results indicated there were linkages between seasonal hydrology, erosion or deposition within a reach, and the coarsening or fining of sediment within a reach in relation to reach-specific locations relative to an existing or removed lowhead dam. There were seasonal differences in sediment deposition and erosion along with coarsening and fining of sediment within a reach. Winter flows were commonly associated with net deposition in reaches while summer flows were connected with net erosion. On the Olentangy River, the trends of fining and coarsening sediment were specific to each reach, and often behaved independently of the patterns of net erosion and deposition. While geomorphic channel changes may be event-driven based on seasonal hydrology, sediment changes may also be a result of the character of the sediment moving through the entire river system and how each reach was able to transport the sediment. On the Scioto River above and below the dam removal, net erosion within the reach corresponded with summer flows and sediment coarsening.

Process-driven geomorphic changes were also noticeable with certain reaches. Within the existing dam impoundment we observed overall net deposition between the first and last survey period (a difference of just over two years), which is consistent with
previous research that lowhead dams are capable of retaining sediment (Csiki and Rhoads, 2010; Rumschlag and Peck, 2007; Stanley and Doyle, 2003). The actively-restored reach upstream of the dam removal had more persistent net erosion occurring during summer and winter flows; this suggests that geomorphic changes are process and event driven within OR3.

Within an urban landscape, the hydrologic regime of rivers is highly altered as a result of increased impervious surfaced, decreased time to peak flows, and higher peak flows (Brabec et al., 2002; Gurnell et al., 2007; Paul and Meyer, 2001). Channel enlargement either through channel widening or incision is a common consequence of the urban river flow regime (Hammer, 1972; Pizzuto et al., 2000). The overall erosion observed at the reaches above dam removal (OR2, OR3, and SR1), below dam removal (OR4), and below an existing dam (SR3) demonstrates the continuation of channel incision as possible result of urbanization and the altered hydrologic flow regime.

3.3 Future Research

Much work has been done to understand how dams affect river systems (e.g., Csiki and Rhoads, 2010; Fencl et al., 2015; Skalak et al., 2009). As dams are being removed, there is a growing need to understand how rivers geomorphically respond within a variety of site-specific conditions. In particular, the physical character of the dam, including dam height and removal method, and how much sediment is stored behind the dam can determine the potential amount of sediment that will move through the system (Csiki and Rhoads, 2010; Grant et al., 2003; Grant and Lewis, 2015; Pizzuto, 2002). The reach scale conditions, including channel morphology, gradient, and channel
bed substrate, and catchment scale characteristics of geology, hydroclimate, and land use, which influence the overarching streamflow and sediment regimes, will also determine the geomorphic response to dam removal (Cheng and Granata, 2007; Csiki and Rhoads, 2010; Grant et al., 2003).

The Channel Evolution Model (CEM) described by Doyle et al. (2002) and Simon and Hupp (1986) describes the six stages of the geomorphic changes within the reservoir upstream of a dam removal. The stages include 1) pre-removal, 2) lowered water surface following dam removal, 3) degradation into the reservoir sediment, 4) degradation and widening, 5) aggradation and widening, and finally 6) quasi-equilibrium. Many dam removals are compared to the CEM and amendments are suggested based on case study observations and conclusions. These modifications are necessary within the ever-evolving science of dam removal. As dam removals are considered for management or restoration options, landowners and officials need to be aware of how the river system could respond based on the site-specific conditions ranging from reach to catchment scale characteristics. When dams are removed, it is critical for geomorphic responses to be monitored in order for the possible variations in results to be added to the growing breadth of knowledge surrounding dam removal.

Our study on the Olentangy and Scioto Rivers emphasizes the need for multi-year monitoring of dam removals in different landscapes, particularly urban landscapes, and also accounting for seasonal hydrology. Furthermore, these observed geomorphic responses, may give insight into the ecological responses observed at the study reaches, in response to the lowhead dam removals.
3.4 Literature Cited


Bibliography


Harris, N., Evans, J.E.J., 2014. Channel evolution of sandy reservoir sediments following
low-head dam removal, Ottawa River, Northwestern Ohio, USA. Open J. Mod. Hydrol. 4, 44–56.


Appendix A – DEM and DOD Figures

Figure A.1 DEMs (top row) and DoDs (bottom row) for OR1, upstream of existing dam. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction.
Figure A.2 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven OR1 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicated deposition.
Figure A.3 DEMs (top row) and DoDs (bottom row) for OR2, passively-restored reach upstream of removed dam. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction.
Figure A.4 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven OR2 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicated deposition.
Figure A.5 DEMs (top row) and DoDs (bottom row) for OR3, actively-restored reach upstream of removed dam. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction.
Figure A.6 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven OR3 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicated deposition.
Figure A.7 DEMs (top row) and DoDs (bottom row) for SR1, restored reach upstream of removed dam. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction. The empty portion is where a bridge crosses the reach.

Figure A.8 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven SR1 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicated deposition.
Figure A.9 DEMs (top row) and DoDs (bottom row) for SR2, reach downstream of removed dam. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction.

Figure A.10 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven SR2 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicated deposition.
Figure A.11 DEMs (top row) and DoDs (bottom row) for SR3, reach downstream of existing dam. Elevation colors grade from low elevation (blue) to high elevation (red). DoDs are bounded by the mask extent of the two sample periods used to calculate them. Elevation change colors are graded from deposition (blue) to erosion (red). Arrow next to first DEM indicates flow direction.
Figure A.12 Histograms of elevation change for every 1-m by 1-m cell in the DoD between the seven SR3 survey time periods. Bars to the left of the grey midline (0-m change in elevation) indicate erosion and bars to the right indicate deposition.
Appendix B – Fixed Points and Overlay of Paired Survey Extents

Figure B.1 OR1 repeat fixed points used for univariate analyses with paired survey extents.

Figure B.2 OR2 repeat fixed points used for univariate analyses with paired survey extents.
Figure B.3 OR3 repeat fixed points used for univariate analyses with paired survey extents. Different color borders are used for June 2013 – September 2013 pairing to more clearly display survey extents.

Figure B.4 OR4 repeat fixed points used for univariate analyses with paired survey extents.
Table B.1 Total number of repeat fixed points within a study reach and the number (and percent of total) of shared points between paired surveys. On the Olentangy River, shared points represent on average 75% (± 17%) of the overall points in an individual survey. Analysis of Scioto River reaches used repeat points which were shared between the three surveys.

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Figure C.1 Sub-reach samples and reach-scale D50 and D84 for OR3 and OR4.
Figure C.2 Sub-reach samples and reach-scale D50 and D84 for SR1, SR2, SR3.
Figure C.3 Change in local slope of select Olentangy River riffles over time. Number below the boxplot indicates the number of local slopes within the longitudinal profile.