EFFECTS OF ARTIFICIAL HABITAT STRUCTURES ON STREAM MORPHOLOGY AND BROOK AND BROWN TROUT IN THE NORTH BRANCH OF THE AU SABLE RIVER, MICHIGAN

By

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ABSTRACT

EFFECTS OF ARTIFICIAL HABITAT STRUCTURES ON STREAM MORPHOLOGY AND BROOK AND BROWN TROUT IN THE NORTH BRANCH OF THE AU SABLE RIVER, MICHIGAN

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Efforts to improve habitat for fish, particularly salmonids, have a long history and intervention is extensive and ongoing. Resource managers and practitioners spend considerable time and money implementing stream habitat projects. Installation of artificial habitat structures is a consistently popular approach. In this thesis I describe effects of artificial structures on stream morphology and fish density and highlight management implications. In the first chapter, I address the effects of habitat structures on stream morphology in a low-power system. Formal evaluations of the effects of habitat structures on stream morphology in low-power systems like the North Branch of the Au Sable River have been very limited relative to the popularity of these projects. I demonstrate that while artificial structures produce some desired habitat characteristics, their effects tend to be localized and may be outweighed by deposition. In the second chapter, I evaluate the relationship between the density of Brown Trout (*Salmo trutta*) and Brook Trout (*Salvelinus fontinalis*) relative to the density of artificial structures. While there are significant relationships for both species, responses are highly variable, and differ by species and size in relation to structure type. I also show the influence of stream context on relationships between fish and artificial structures.

ACKNOWLEDGMENTS

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Members of the Hayes Lab contributed to my research and helped improve the quality of my writing. Jason Smith provided extensive, invaluable edits to both chapters presented here, as well as feedback for my presentation. Dr. Corrine (Corey) Higley and Mitch Nisbet were members of my field crew in the first year, with Corey providing special assistance as she had previously conducted research in the Au Sable River. Jason and Corey provided moral and personal support during my graduate studies and beyond, and my relationship with them, Dr. Hayes, and other fisheries and wildlife folks is one of the most cherished outcomes of my university experience. Hailey Yondo

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Effects of artificial habitat structures on stream morphology in the North Branch of the Au Sable River, Michigan

Introduction

River habitat projects often seek to increase heterogeneity in streams and mitigate the impacts of reduced structural habitat complexity (Roni et al. 2008). According to a meta-analysis by Roni et al. (2008), many projects were intended to ameliorate effects of practices such as dredging or ‘stream cleaning’. In cases where streams have reduced structural complexity due to ‘stream cleaning,’ it was an expectation with strong *a priori* appeal that the installation of artificial habitat structures would mimic the role of naturally recruited woody debris. It is estimated that over US $1 billion are spent each year on habitat projects in streams (Roni et al. 2008). Resource agencies and non-agency practitioners often seek to mitigate habitat degradation and increase fish production through alteration of habitat by placing artificial structures. There is a long history of such intervention and it continues today, particularly for salmonid management. Grant programs have commonly funded projects to add or repair artificial habitat structures in streams, e.g., over $300,000 was allocated in 2014-2015 to support five habitat improvement projects involving adding or repairing artificial habitat structure in Northern Lower Michigan. The expectation is that these structures will provide habitat directly as fish cover, and by increasing the heterogeneity of instream habitat by increasing depth and stream flow (velocity) and maintaining coarser substrates.

A number of studies have evaluated the responses of fish to the installation of artificial structures. Avery (2004) and Roni et al. (2008) provide synthetic summaries of numerous projects conducted across a broad range of stream conditions. Although these studies focused on different species and habitat improvement techniques, each found variability in the response of fish to habitat structures. Roni et al. (2008) provided several potential reasons for cases where there was little or no fish response, including improper size or design of structures, limited durability of installed structures, or failure to account for stream processes in siting, selecting, and implementing the stream habitat improvement projects. Further, they noted that few studies have critically evaluated the implications of artificial habitat structures on fluvial geomorphology, and fewer still have considered both biological and habitat responses (Roni et al. 2002). The paucity of such studies significantly limits the ability of practitioners to identify whether fluvial parameters are driving the variability observed in biological outcomes.

While the literature on instream habitat enhancement is extensive (Roni et al. 2008), formal evaluations of the effects of habitat structures on stream morphology in low-power systems have been very limited relative to the popularity of these projects (Rabini and Jacobson 1993, Roni et al. 2002, Wills and Dexter 2011). Most studies reviewed in the Roni et al. (2008) meta-analysis occurred in Western North America, especially in higher-power coastal streams, while studies of low-power inland systems are relatively uncommon. A similarly-focused review of fish habitat rehabilitation projects using wood, Nagayama and Nakamura (2010), found that of more than a thousand studies associated with wood, only seven of those available in the open literature were in moderately sized streams with low bed gradients.

Expectations from the application of stream habitat techniques in systems with higher stream power may not be met with similar results if those techniques are applied in the context of a low-power system. To help delineate findings from available literature and expectations for stream systems of differing power and structures of various sizes, I am proposing a conceptual framework in the form of a matrix of stream power and structure size and expected resulting stream and habitat characteristics (Figure 1.1).

A proposed conceptual framework for understanding the influence of artificial structures in streams

There are many ways of representing factors that determine how artificial structures influence stream morphology. Two of the primary considerations are the size of the structure and the capacity of the stream to change its morphology. Characterizing the size of structures is difficult and has been approached in several ways (Avery 2004, Braudrick and Grant 2001, Cozad 1992, Hunt 1993). I focus on the size of structure relative to stream width, because it is consistent across structure types, and has a more direct relationship to stream function and processes than other approaches (Figure 1.1).

Among several possible factors influencing the ability of streams to evolve channels, (e.g., hydrologic pattern, stream gradient, stream discharge, catchment area, geologic material, physiographic province), I selected stream power (Figure 1.1), which integrates several of these factors. From a hydraulic standpoint, structures would be expected to elicit a different response depending on stream power (Buffington et al. 2002). Stream power mediates both stream capacity, the total amount of sediment particles a stream can convey, and stream competence, the largest sediment particle sizes a stream can move. In higher-power systems, installation of large structures (Figure 1.1, cell D) has the potential to reshape channels and alter channel unit size and bedform morphology, leading to the maintenance of larger, deeper, or more frequent pools (Nichols and Ketcheson 2013). In addition, these higher-power systems tend to have the capacity to continue to transport displaced materials, leading to maintenance of coarser streambed sediments and less deposition (Mueller and Pitlick 2005).

While many studies, including mine, have included a range of structure sizes, most were conducted in higher-power systems as described in the summaries of scope for Roni et al. (2008) and Nagayama and Nakamura (2010). Based on the findings in those reviews, as well as the results in previous work on low-power systems (Frissel and Nawa 1992, Muotka and Laasonen 2002, Pretty et al. 2003, Quinn 1994) and Avery (2004) which is described in further detail below, it is unclear whether expectations based on studies of higher-power systems will hold for low-power systems.

Avery's (2004) review provides case studies of low-gradient and intermediate-gradient streams with a suite of techniques for altering instream habitat. These case studies did not always document physical changes to streams (often this is not done), but when summaries included physical parameters, the results were described variously as: increased depth in treatment zone, decreased stream width in treatment zone, increase in "under bank holding cover," "overhead bank cover," increase in number of pools, or increase in pools of certain depths. This review also provides helpful diagrams showing the relative scale of structures to the stream. Current deflectors and whole log cover structures were shown spanning most of or a substantial fraction of the stream in the diagrams. These studies, overall, suggest the creation of some pool habitat, but of limited longitudinal extent. The studies reviewed by Avery involved habitat alterations involving larger structures, including different types of structure compared to the efforts documented in my study, and are representative of the scenario in cell B of the matrix (Figure 1.1). As such, the expectations outlined in cells A and B of the matrix can be viewed as a set of *a priori* hypotheses based on the literature that my research is intended to evaluate.

Possibly the best example of small structures in a high-power system (Figure 1.1, cell C), is the addition of boulders to high-gradient streams. These typically are not associated with any deposition (the flows in high-gradient streams typically lead to high capacity for sediment transport, especially of finer particles), but can create 'pocket pools." Similarly, Hunt (1993) included a few high-gradient structure designs in his guide for practitioners, including some which were relatively small (e.g., piers), but which were expected to create lateral pools or other microhabitat.

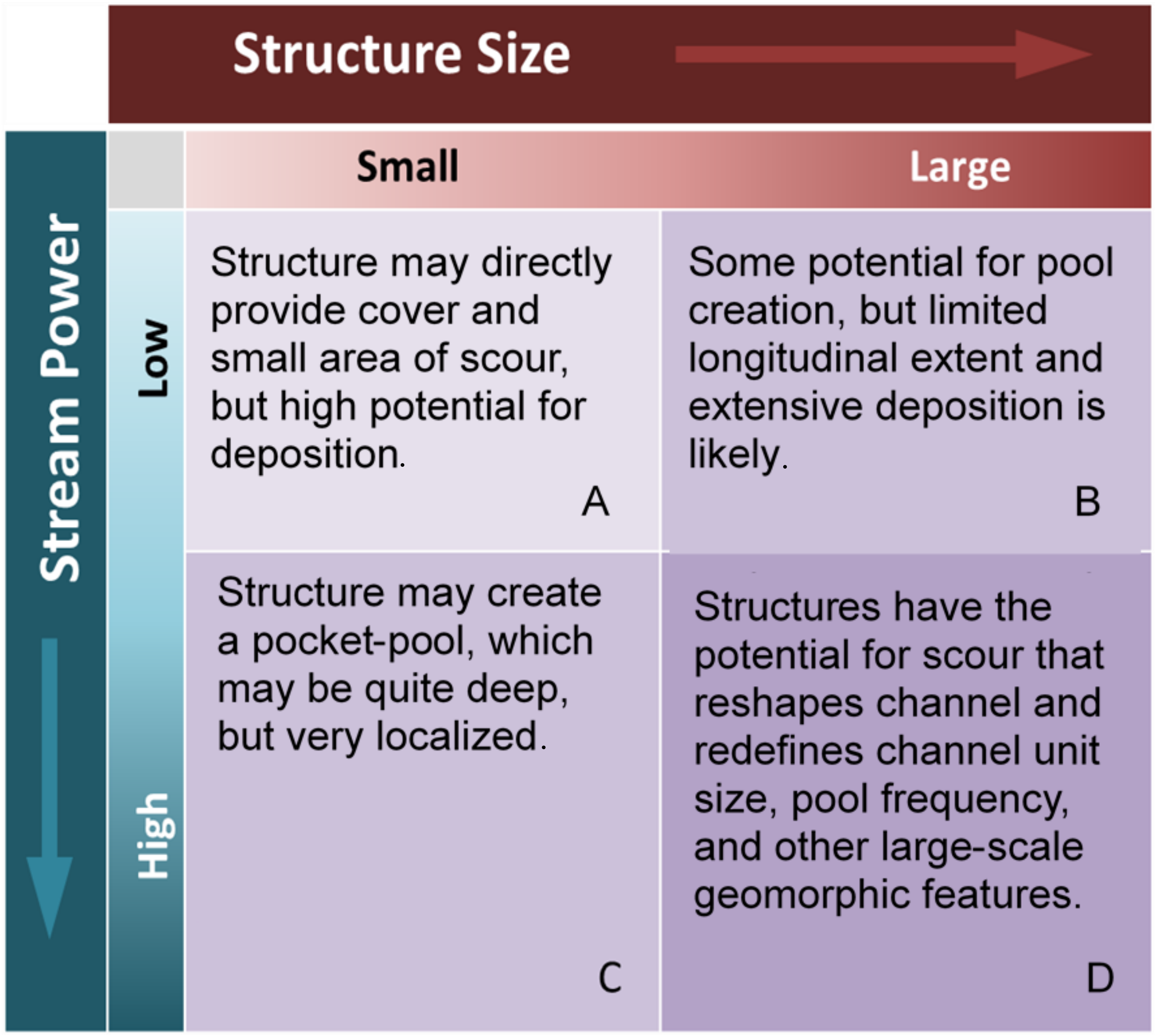

Figure 1.1: Conceptual framework for understanding influence of stream power on structure size and associated habitat and stream process implications. Large structures are those that span 30% or more of the stream width and are represented in cells B and D, while smaller structures are in cells A and C.

Studies of the relationship between habitat structures and stream morphology at the lower end of the range of hydraulic conditions (stream power, stream gradient, flashiness) are very limited compared to those in higher-gradient streams, as outlined earlier. My study adds to the habitat literature by focusing on a low-power system in which structures ranging from small to large (greater than 30-40% of stream width) were placed.

Most Michigan streams are low-power systems (Brenden et al. 2008, Seelbach et al. 1997, Wehrly et al. 2006), and a study in Michigan would help address the paucity of information on such systems, while directly addressing a site of management interest in proximity to many other similar stream systems. The North Branch of the Au Sable River is classified as relatively low gradient (Wang et al. 1998), and dominated by groundwater baseflow, which contributes to its stable flow regime. Many Midwest trout streams share similar hydrologic features (low-power, groundwater dominant) and are subject to similar efforts to alter stream conditions to benefit trout by adding artificial habitat structures. The North Branch of the Au Sable River has undergone significant and sustained efforts to alter physical in-stream habitat and morphology by installing artificial habitat structures, making it an appropriate site for studying the effects of these structures.

In this system, and many low-powered stream systems like it, efforts to improve fish habitat have not been accompanied by follow-up investigation and observation. In contrast to the substantial body of literature for high-gradient streams or that focus on fish response, little research is available to provide insights about the physical habitat characteristics associated with artificial habitat projects. The habitat component of this study seeks to provide information on the effects of artificial habitat structures that are installed to provide cover and increase heterogeneity of instream habitat (i.e., depth, scour, coarse substrates, higher point velocity) in a low-power system.

The goals of my study (in this Chapter) are:

a) Determine whether artificial structures increase depth, point velocities, and the prevalence of coarse substrates in a low-power system, and if so, to what extent

b) Compare the patterns I observed in this low-power system to findings from other river systems and

c) Evaluate how this relates to our understanding of fluvial geomorphology.

Methods

I first examined a subset of structures in greater detail as case studies to identify the prevailing processes and to guide analysis of data aggregated across structures. I then examined responses aggregated across all structures to determine whether and to what extent patterns in depth, velocity, and substrate particle size in the case studies could be generalized beyond the case studies and conformed to my conceptual model (Figure 1.1). The aggregated data provided information across a larger number of structures. Thereby incorporating more variability associated with different sites and configurations.

Study Site

The North Branch of the Au Sable River in Michigan (Figure 1.2) is a low-power stream system, with low gradients (Wang et al. 1998) and groundwater dominated hydrology. It flows through glacial outwash deposits (Zorn and Sendek 2001) and has primarily gravel and sand substrates within the channel. It is representative of many other groundwater-dominated streams in the Northern portion of Michigan's Lower Peninsula sharing many of their physical and biological characteristics. In addition, there is a high level of social, economic, and recreational interest in the North Branch. Its history of extensive habitat management efforts made it a suitable site for this study.

The study included 11 sites along a 33 km section of the North Branch (Figure 1.2). Site selection was determined in part by ease of access but sought to include the range of artificial structure density, depth, velocity and temperature conditions found in the river. Because of the low gradient and consistent flow of the North Branch, the range of habitat conditions available for study was relatively narrow (Table 1.1). Within the 11 sites three case study sites were identified and sampled in greater detail.

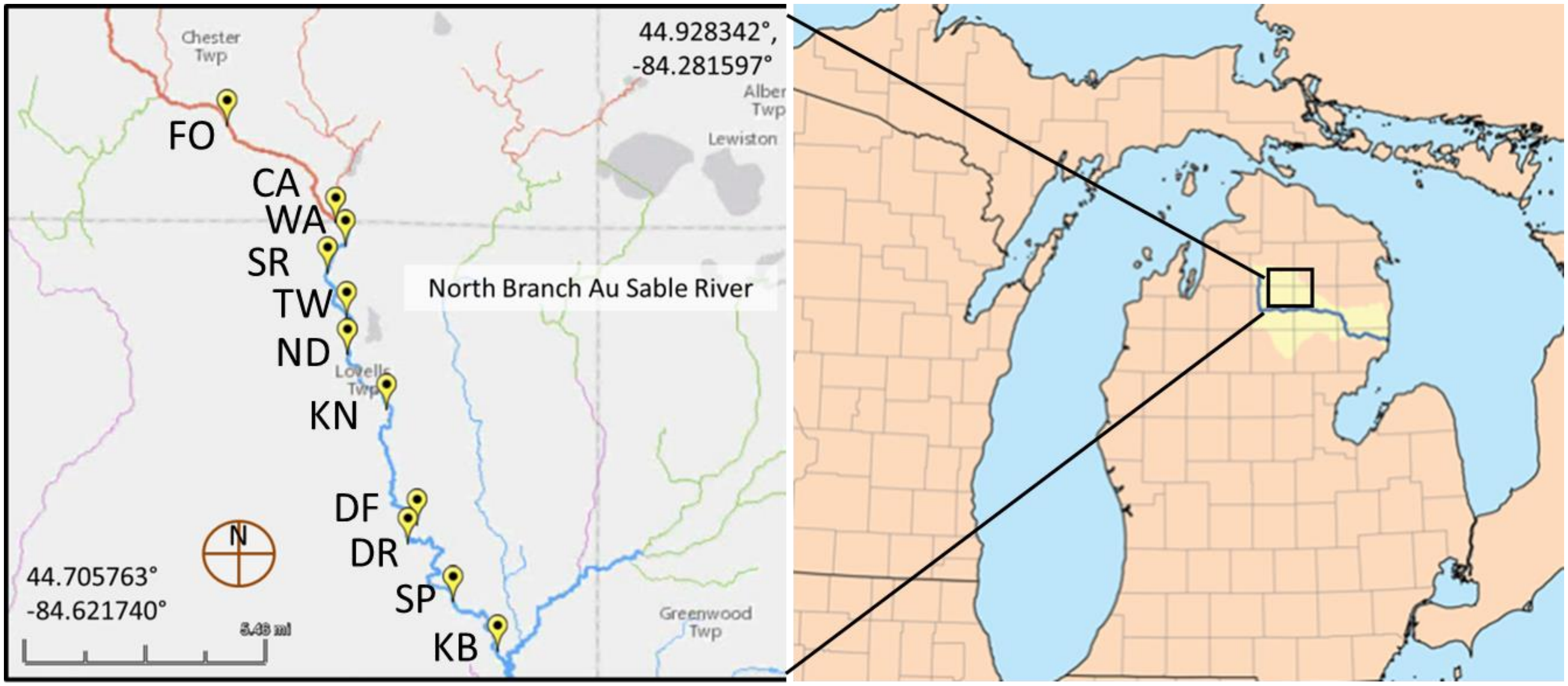

Figure 1.2. Study Sites: Left: North Branch of Au Sable River study area. Sites surveyed in the North Branch are marked with yellow pins and two character site identifiers (KB=Kellogg Bridge access point). The North Branch and its tributaries are colored according to thermal classification (red=warm, blue=cold-transitional, green=warm-transitional, purple=cold). Right: map of Au Sable River watershed (highlighted in yellow).

Habitat and Stream Morphology Sampling

Inventory of habitat in the North Branch

To determine how sites selected for fish and habitat sampling compared to the broader context of the North Branch of the Au Sable River, a census of artificial habitat structures, stream width, point-depth, water temperature, bank conditions and other features was conducted for 33.5 km of the stream. The North Branch was broken into 150 m or 300 m sections and the conditions within each section, including counts of structures, were recorded. That census noted over 1100 structures, with densities ranging from 0 per 300 m to 31 per 300 m. A total of 92 structures were noted within the site boundaries of the 11 sites.

Transect data

Prior to conducting habitat surveys, transects were set up to assess the effect of the structures. This typically involved two transects upstream of the structure, one or more transects at or through the structure, and two transects downstream of the structure. Where possible, the upstream-most transect was intended to serve as a reference transect representing minimal or no influence of the structure. Sometimes, transects intended to act as upstream controls were within the influence of other upstream structures and could not be used for this purpose. In circumstances where structures were positioned without obvious confounding factors (especially the influence of other structures nearby or morphological changes like confluences from tributaries), additional transects were set up to support case studies.

Transect set-up

Each transect began onshore far enough to firmly secure a fiberglass measuring tape. The water's edge on the left bank was marked as zero. A Topcon AT-G4 auto-level was set up at each site above benchmarks in order to measure streambed elevation. On repeat visits, the tape was placed in the same manner and the water's edge marked again. Because the system has very stable flows (Wang et al. 1998), the water's edge was within about 0.05 m or less between surveys for sites that were visited repeatedly.

Point sampling

Each transect was divided into about 20 evenly spaced sampling locations (Figure 1.3). At each point, streambed elevation (feet relative to the arbitrary datum of benchmark), depth (m), water temperature (°C), velocity (m/s) and dissolved oxygen (mg/L) were recorded. A blind-touch method was used to characterize streambed composition, using five observations per point. The blind-touch method involved personnel standing with one foot adjacent to the sample point while reaching toward the substrate near the toe of his/her boot with one hand and measuring the first object he/she touched. A modified Wolman (1954) method was used for characterizing the sediments observed in the substrate sample. Sediment particles greater than 4 mm diameter along the intermediate axis ("pebbles") were measured to the nearest mm and the value was recorded. If organic material or other non-pebbles were encountered, they were noted under the following categories: vegetation, organic debris (e.g., leaves), muck, or woody debris. Observations of sediments less than 4 mm in diameter were classified by hand texturing as clay, silt, fine sand, or sand (Kondolf and Li 1992).

For sample locations where the depth was greater than an arm's length (0.7 meters, which occurred infrequently), a mechanical grab of the substrate was employed in which a shallow scoop with a fine net was pulled in the direction of the current and upward from the bed surface; the blind-touch method was used within that bulk sample. Temperature and dissolved oxygen was measured using an YSI Pro ODO (Optical Dissolved Oxygen) Meter. Although dissolved oxygen was measured, it was so closely correlated with temperature that it was dropped from the analysis. Moreover, mean oxygen concentrations were always greater than 7 mg/L, which should not be limiting to trout (MDEQ 2006).

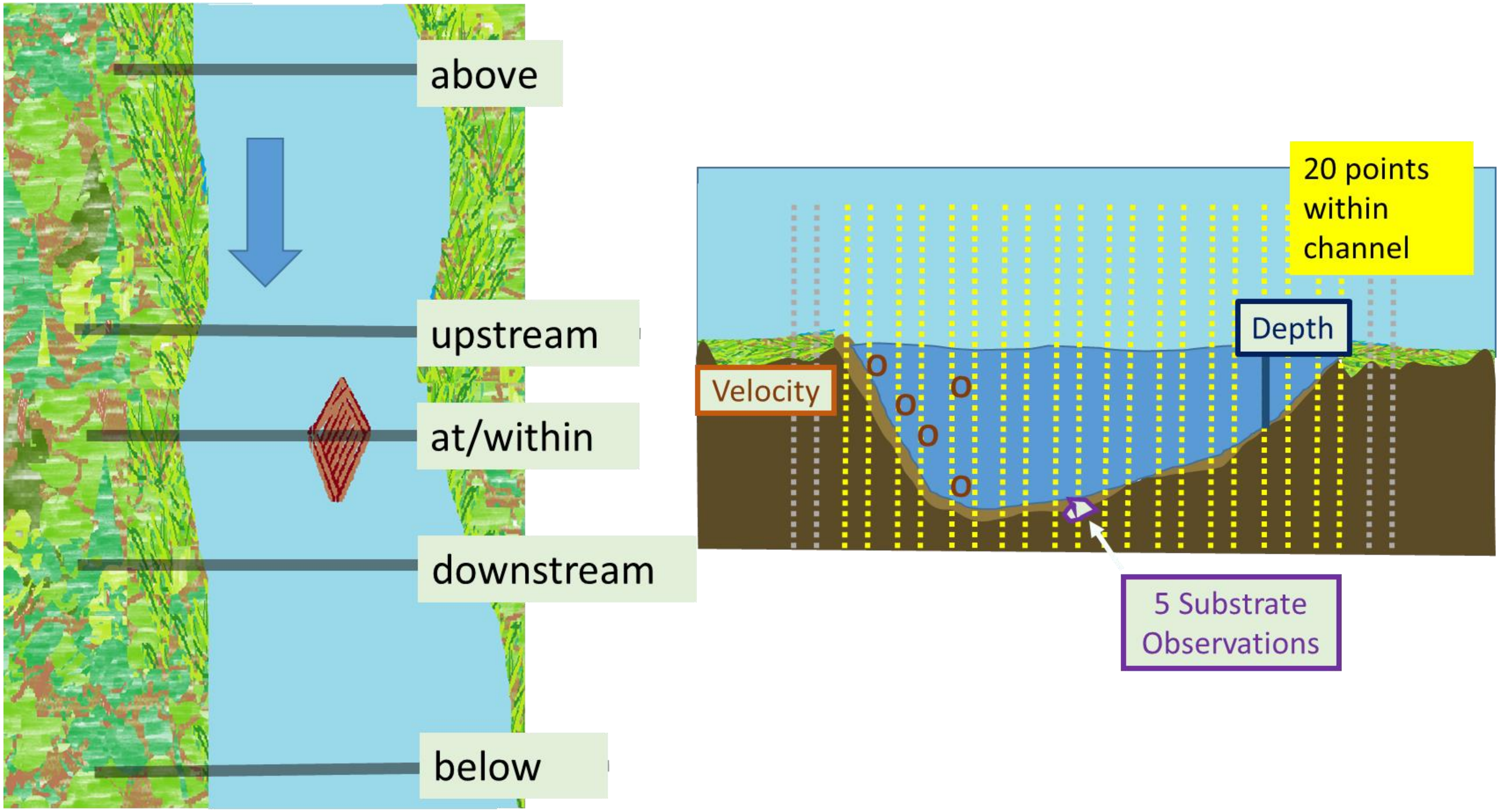

Figure 1.3: Generalized illustration of transect category by position relative to artificial structure. Rhomboid figure represents an artificial habitat structure. The panel to the right illustrates the point sampling strategy within each transect.

Case Studies

The intent of the case studies of individual structures is to provide examples that illustrate some of the complexities in the analysis of data aggregated across all structures, as well as to provide concrete examples to discuss how stream processes were affected by the structures and to provide insight into what might be underlying these patterns. My case studies focused on structures for which there was sufficient transect level data to characterize the spatial scope of potential structure influence on depth, substrate particle size, and velocity in the vicinity of their placement. The three case studies I selected represent common configurations in circumstances that were representative of stream conditions across multiple sites. At each case study structure, a higher density of points were collected, however the data collection was consistent with the broader habitat sampling strategy. Case studies offer an opportunity to tease apart the complexity underlying an overall assessment, and outline the process used to develop aggregate measures of impact.

Aggregate measures of structure effect

Data from transects were combined according to transect position relative to a structure longitudinally (in the upstream/downstream direction). Transects were initially categorized according to the longitudinal designations used in Figure 1.3, based on insights gained from the case studies. Boundaries for categorizing transects were as follows: 1) all transects that traversed a structure or were within 1 meter upstream were categorized as “at”; 2) transects which were less than 10 m downstream of a structure were categorized as “downstream,”; 3) transects which were greater than 10 meters downstream were categorized as “below”; and 4) transects more than 1 meter upstream of a structure were categorized as "above." For velocity and substrate texture, insufficient point measurements were available to distinguish the four categories outlined above, so three were used; "at", "downstream", and "outside" a new category which combined the transects previously categorized as "above" and "below."

Similarly, the influence of structures on the stream is not evenly distributed laterally across the stream width. In most cases, the stream adjusts around the structure and the structure has a diminished effect with increasing lateral distance. To characterize the effect of a structure on its immediate vicinity, accounting for the different stream widths and structure sizes observed, points laterally along a transect were grouped according to percent of stream width away from the structure (Figure 1.4).

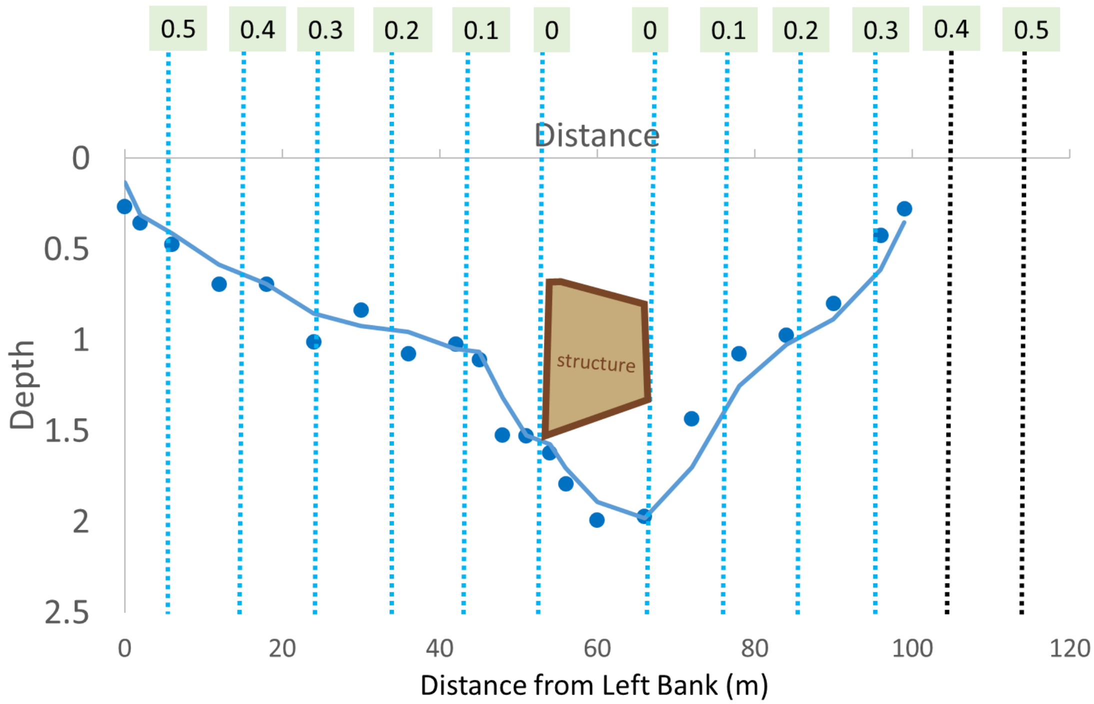

Figure 1.4: Points binned according to lateral distance across stream width, adjusted for structure placement. The structure is represented by a brown polygon located near the center of the stream. Points located within the width of the structure are categorized as "within" and points outside the structure footprint are grouped according to the percent of stream width away from the structure, where 0 is at the edge of the structure and 0.5 is the furthest bank of the stream. Points equidistant from the structure laterally were placed into the same bin for the analysis. Because of the influence of the shore on habitat conditions, analysis was limited to points within 20% of stream width from the structure.

Results

Representative habitat conditions observed at each site may be useful for understanding relationships observed (Table 1.1). For example, mean depth was limited to a relatively narrow range across all sites, 0.26 to a maximum of 0.51 m. The 90th percentile depth at the deepest site is still less than 1 m. Mean velocity for many sites was around 0.3 m/s, but ranged from 0.15 m/s to a high of 0.77 m/s. There is a larger difference between the 90th and 10th percentiles for velocity compared to depth. Median temperature was also observed within a narrow range, from 15.5 – 20.5 °C, with sites of relatively high median temperature also including observations of cooler water temperatures. Most sites had median water temperatures less than 19.5 °C, which as a mean July stream temperature would correspond to a “cold-transitional” stream classification; observation of water temperature at all sites included 10th percentile values of less than 17.5 °C which, if observed as a July mean temperature, would correspond to a “cold” stream classification (Wehrly et al. 2006).

	Depth (m)						Velocity (m/s)						Temperature (°C)					
				Percentile						Percentile						Percentile		
Site_ID	n	mean	variance	10th	median	90th	n	mean	variance	10th	median	90th	n	mean	**variance**	10th	median	90th
FO	333	0.257	0.012	0.122	0.247	0.405	151	0.21	0.03	0.01	0.20	0.46	320	17.24	2.31	15.24	17.58	18.97
CA	260	0.418	0.033	0.152	0.405	0.664	230	0.15	0.01	0.02	0.12	0.31	253	19.29	6.94	14.66	20.53	21.73
WA	119	0.399	0.051	0.149	0.341	0.713	103	0.36	0.04	0.06	0.39	0.58	117	15.95	0.66	15.37	15.89	17.17
SR	408	0.363	0.027	0.152	0.366	0.567	187	0.33	0.04	0.08	0.30	0.56	347	17.71	2.10	15.36	17.95	19.74
TW	296	0.330	0.012	0.168	0.323	0.457	298	0.35	0.05	0.02	0.38	0.60	295	19.02	2.49	16.57	19.50	20.53
ND	800	0.279	0.018	0.104	0.279	0.451	754	0.28	0.04	0.00	0.30	0.51	640	15.93	5.07	13.59	15.58	18.71
KN	182	0.340	0.033	0.137	0.299	0.646	172	0.43	0.06	0.11	0.43	0.74	180	15.82	1.56	14.12	15.86	17.26
DF	180	0.447	0.024	0.191	0.463	0.622	177	0.77	0.15	0.14	0.78	1.24	181	19.18	6.40	16.37	19.66	22.58
DR	354	0.396	0.054	0.146	0.372	0.686	104	0.23	0.03	0.05	0.18	0.49	356	15.64	1.13	14.59	15.52	16.93
SP	265	0.514	0.080	0.186	0.463	0.914	176	0.36	0.05	0.01	0.37	0.66	186	16.52	1.48	15.23	16.26	18.24
KB	720	0.428	0.051	0.145	0.418	0.744	211	0.41	0.06	0.10	0.39	0.73	704	16.49	0.64	15.53	16.47	17.26

Table 1.1: Habitat conditions across sites within the North Branch of the Au Sable River, MI. Sites are arranged from upstream (top) to downstream (bottom of table). The number of point measurements within each site, combining 2014 and 2015 is represented by n.

Case Study 1: Sheep Pasture Site

My first case study of river morphological adjustment is of an artificial structure around which deeper water and higher point velocities were observed with minimal deposition in the downstream area. This artificial cover structure is located at site SP, the Sheep Pasture fishing access point (Figure 1.2, second-most downstream point). This site represents a relatively simple situation, with no other artificial structures nearby and a relatively small "footprint." This structure is a log-sod island located at the downstream end of a relatively straight reach of the river, but the river bends immediately downstream of the structure (Figure 1.5). The structure is relatively narrow in width (about 2 m) relative to the channel width (about 20 m) and has its longest edge oriented parallel to the flow (Figure 1.6).

There were five transects located in the immediate vicinity of this structure (Figure 1.6). Transect A was located about 18 meters upstream of the structure, above its apparent influence zone. The depth profile shows the thalweg was near the right bank (Figure 1.6, depth panel, row 1), with a mean depth of 0.38 m, with a standard deviation of 0.14 m. The velocity profile at this transect (Figure 1.6, velocity panel, row 1) was u-shaped and roughly symmetrical with a mean velocity of 0.40 m/s and a standard deviation of 0.24 m/s. The profile of mean pebble diameter reflected the bend-pool morphology, with the largest particle sizes occurring near the center of the channel (Figure 1.6, substrate panel, row 1). The mean particle size for the transect was 15 mm with a standard deviation of 13 mm.

Transect B was located 4.5 m upstream of the structure (Figure 1.6) and represents a transition from a bend-driven channel shape, to the beginning of the effect of the structure (Figure 1.6, depth panel, row 2). Overall, the depth profile was similar to Transect A, with the thalweg near the right bank, with a mean depth of 0.39 m and a standard deviation slightly higher at 0.20 m. Likewise, the velocity profile at Transect B was similar to Transect A, with a mean velocity of 0.37 m/s and a standard deviation of 0.21 m/s. Sediment size was greatest near the center of the channel with a roughly unimodal distribution (Figure 1.6, substrate, row 3). The mean particle size was 16 mm and the standard deviation was 13 mm.

Transect C was located at the apex of the structure (Figure 1.6, left), and showed some influence of the structure. Depths were greater (mean = 0.47 m) and more variable at this cross-section (standard deviation = 0.32 m) than upstream, (Figure 1.6, depth panel, row 3 vs row 1 and 2). In contrast to the u-shaped velocity profiles at Transect A and B, the velocity profile at Transect C was m-shaped, with an area of diminished velocity at the apex, flanked by relatively faster areas on either side (Figure 1.6, velocity panel, row 3). The net effect was that the mean velocity was lower at Transect C (mean = 0.30 m/s, standard deviation = 0.16 m/s) than any other transect at this site. Sediment size was highest near the middle of the channel (Figure 1.6, substrate panel, row 3). The mean particle size was similar to the two upstream transects, averaging 16 mm with a standard deviation of 16 mm.

Transect D was located approximately 3 m downstream of the apex of the structure, bisecting the structure (Figure 1.6, left). The structure contained gaps between the logs, allowing water to inundate the lower part of the structure. The overall channel profile at this transect was u-shaped, with a greater mean depth (0.56 m) relative to upstream transects. The mean and variability in velocity at Transect D (mean = 0.37 m/s, standard deviation = 0.21 m/s) was similar to Transects A and B. Sediment particle size was larger at this transect (mean = 28 mm, standard deviation = 15 mm) than the previous transects.

Transect E was located approximately 6 m downstream of the terminus of the structure (Figure 1.6, left). The overall channel profile at this transect was u-shaped (Figure 1.6, depth panel) with the highest mean depth (0.70 m) at this site. The mean velocity (0.39 $\pm$ 0.25 m/s) for Transect E was similar to transects above the structure. The profile of sediment sizes indicates a depositional area in the center of the channel (i.e., the dip in the distribution in Figure 1.6, substrate panel, row 5), but the overall mean particle size was largest at this transect at 31 mm.

Overall, this structure appears to have promoted some degree of channel scour, leading to a deeper area adjacent to the structure, more heterogeneity in water velocity, and localized scouring adjacent to the structure but very little deposition downstream of the structure. As such, the impact of this structure broadly fits within quadrants A and C of Figure 1.1.

Sheep Pasture

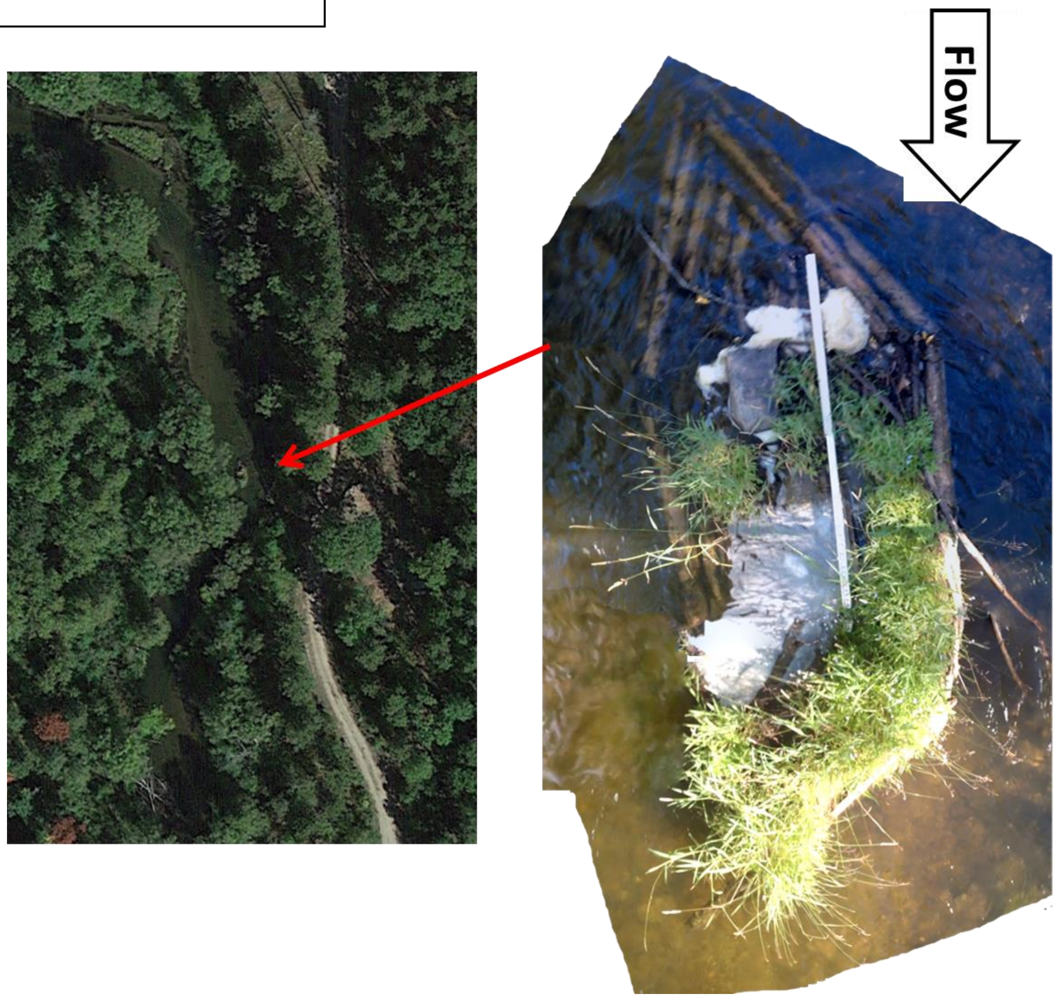

Figure 1.5: Satellite image of Sheep Pasture reach (left) and close-aerial photo of cover structure (right). The photo at right shows a six-foot stadia rod (white) oriented roughly parallel to stream flow for scale.

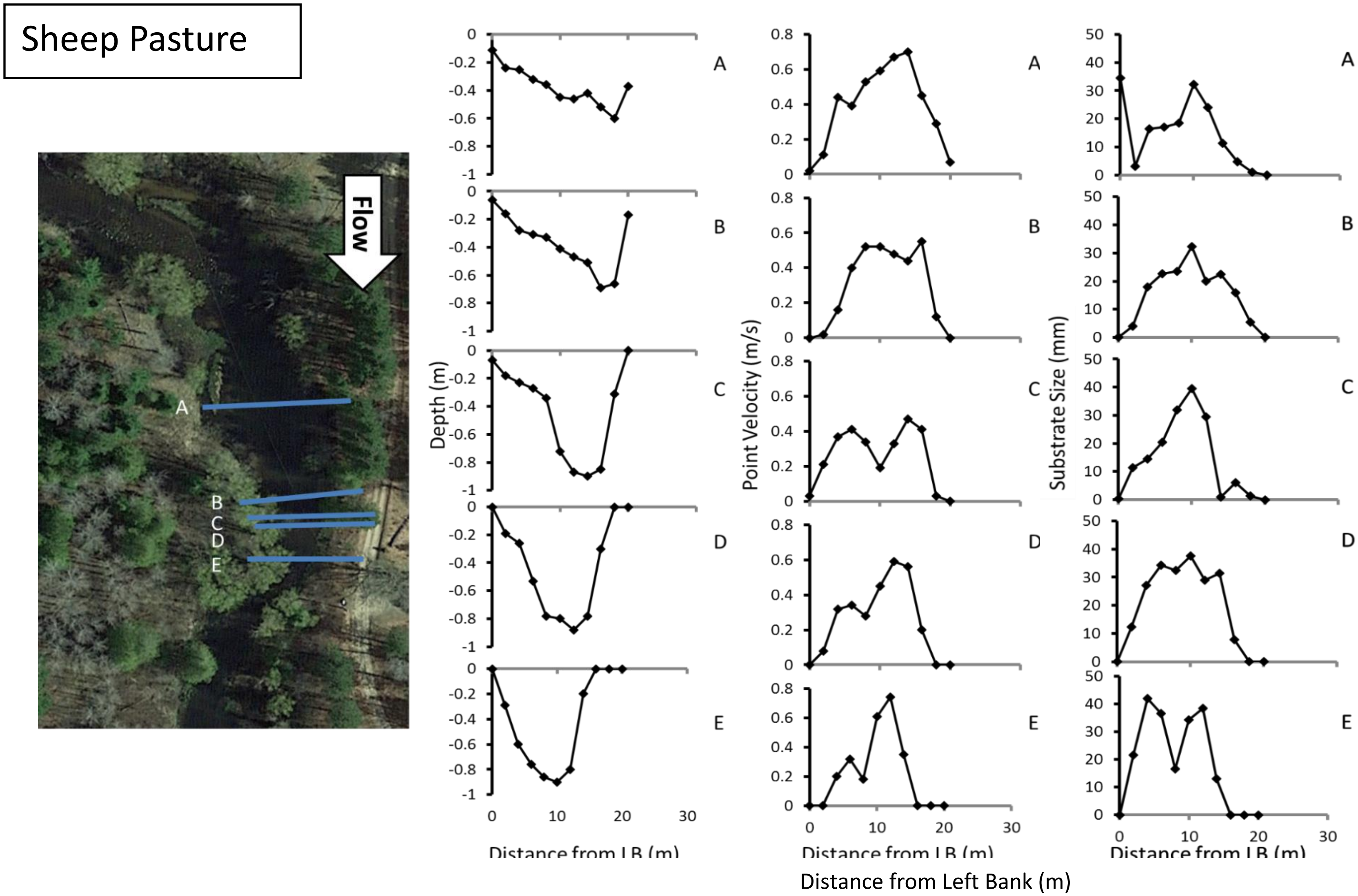

Figure 1.6: Sheep Pasture: Case study of artificial cover structure. Transect measures of depth, point velocity, and substrate size featured in panel of graphs. Top row of panel: graphs labeled A show point data for transect A.

Case Study 2: Powerlines Site

A wing deflector at the Powerline site highlights depositional features I observed associated with some structure designs and configurations. Deflector structures are often installed to create scour. This instream structure altered the distribution of depth and point velocity and increased heterogeneity of the substrate. The structure includes multiple logs arranged in a wide v-shape, with the narrow angle pointing upstream and wings trailing toward the streambanks (Figure 1.7). The structure showed multiple breaches throughout its length (Figure 1.7). In contrast to the structure at Sheep Pasture, which is narrow relative to the stream channel and does not have associated depositional features, the wing deflector at this site spanned nearly the entire stream width (Figure 1.7). There were four transects associated with this structure, which are illustrated in Figure 1.8.

Transect A was located within approximately 1 m above the structure apex and within the influence of the structure (Figure 1.8). Mean depth at this transect was 0.30 m with a standard deviation of 0.18 m. The channel was roughly w-shaped, (Figure 1.8, depth panel), showing an asymmetrical velocity profile that included two main areas of flow, one hugging a bank, the other broken up but occurring across about half of the channel width offset from the opposite bank (Figure 1.8, velocity panel, row 1). The mean velocity at Transect A was 0.22 m/s, with a standard deviation of 0.20 m/s. The distribution of sediment sizes reflected the depositional area below this structure, with the largest particle sizes occurring near the outside edges of the channel (Figure 1.8, substrate panel) coincident with areas of peak velocity. The mean particle size was 6 mm and the standard deviation was 6 mm.

Transect B was located within the wings of the structure, a few meters downstream of the apex of the structure (Figure 1.8.) The consequences of the flow barrier created by the structure are more pronounced, with depths approaching zero (Figure 1.8, depth panel, row 2) and finer substrate noticeable (Figure 1.8, substrate panel, row 2) near the center of the channel. The overall depth (mean depth = 0.32 m) and variability (standard deviation = 0.21 m) at this transect were similar to Transect A. The velocity profile at Transect B was more heterogeneous and included a peak toward the left bank (the highest observed point velocity) (Figure 1.8, velocity panel, row 2). The mean velocity for Transect B was 0.30 m/s, with a standard deviation of 0.43 m/s. Similar to Transect A, the largest particles occurred near the outside edges of the channel, with very fine sediments occupying the middle of the channel (Figure 1.8, substrate panel). The mean particle size and standard deviation of particle size was about 50% larger than Transect A: 9 mm and 9 mm (Figure 1.8, velocity panel, row 2 with row 1).

Transect C was located 1.5 m downstream of the structure (Figure 1.8), and redistribution of the stream along each side of the structure was evident, with a continuation of the w-shaped cross section and deeper areas originating along the structure as observed in Transect B. Mean depth (0.33 m) and standard deviation (0.22 m) were almost identical to Transect B. The velocity profile in Transect C included three peaks, with the fastest point velocity at the channel edges (Figure 1.8, velocity panel, row 3) and a minor peak near the center. The mean of the velocities for Transect C was 0.33 m/s, with a standard deviation of 0.258 m/s. Sediment size distribution again showed higher particle diameters near the edges of the channel (Figure 1.8, substrate panel, row 3). The mean particle size (12 mm) and standard deviation (11 mm) were the highest of any transect at this site.

Transect D was located approximately 18 m downstream of the apex of the structure (Figure 1.8). The overall channel profile was more uniform than upstream transects, with minor deeper areas near the edges of the channel Figure 1.8, depth panel, compare row 4 to rows 1-3). Mean depth was lower than other transects, at 0.24 m, and variability in depth was much smaller at 0.09 m. The velocity profile in Transect D was distributed more broadly, with the exception of a low-velocity region in the center of the channel associated with the tail of the depositional area downstream of the structure (Figure 1.8, velocity panel, row 4). The mean of the velocities for Transect D was 0.31 m/s with a standard deviation of 0.180 m/s. Sediment size followed a similar pattern as velocity, with the depositional area reflected in finer sediment sizes across a narrow band of points (Figure 1.8, substrate panel, row 4). The mean particle size (9 mm) and standard deviation (8.08 mm) of mean particle sizes was intermediate to Transect A and Transect B.

In summary, the patterns observed in water depth, velocity, and substrate size associated with this structure fit my a priori hypotheses expressed in cell B of Figure 1.1. This structure led to localized scour with deeper water and higher velocity in immediate vicinity of the structure, but also lead to extensive deposition of fine material in the wake of the structure.

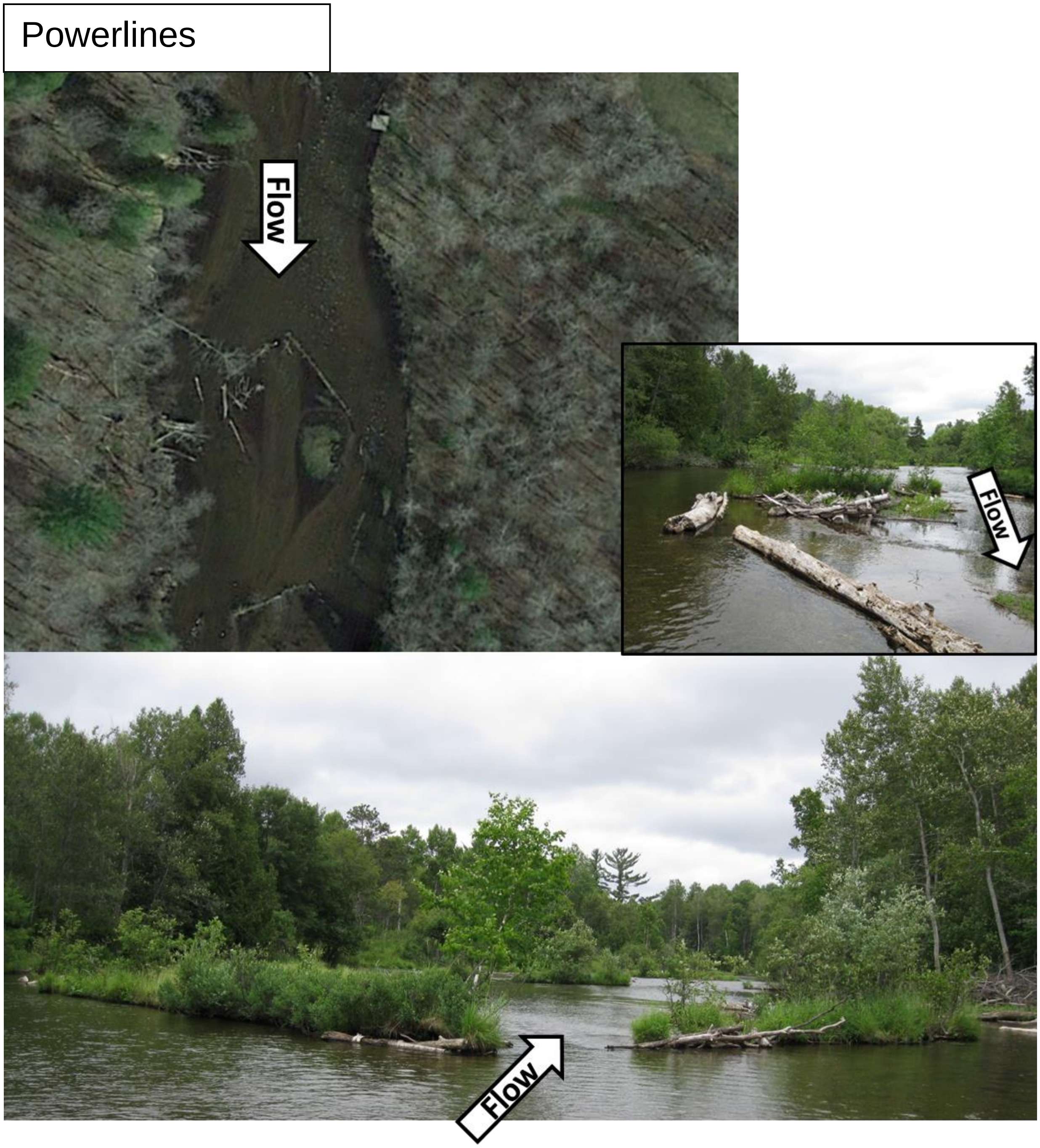

Figure 1.7: Satellite image of Powerlines site (left, top) close-up photos of scour structure (middle right facing north, bottom facing south).

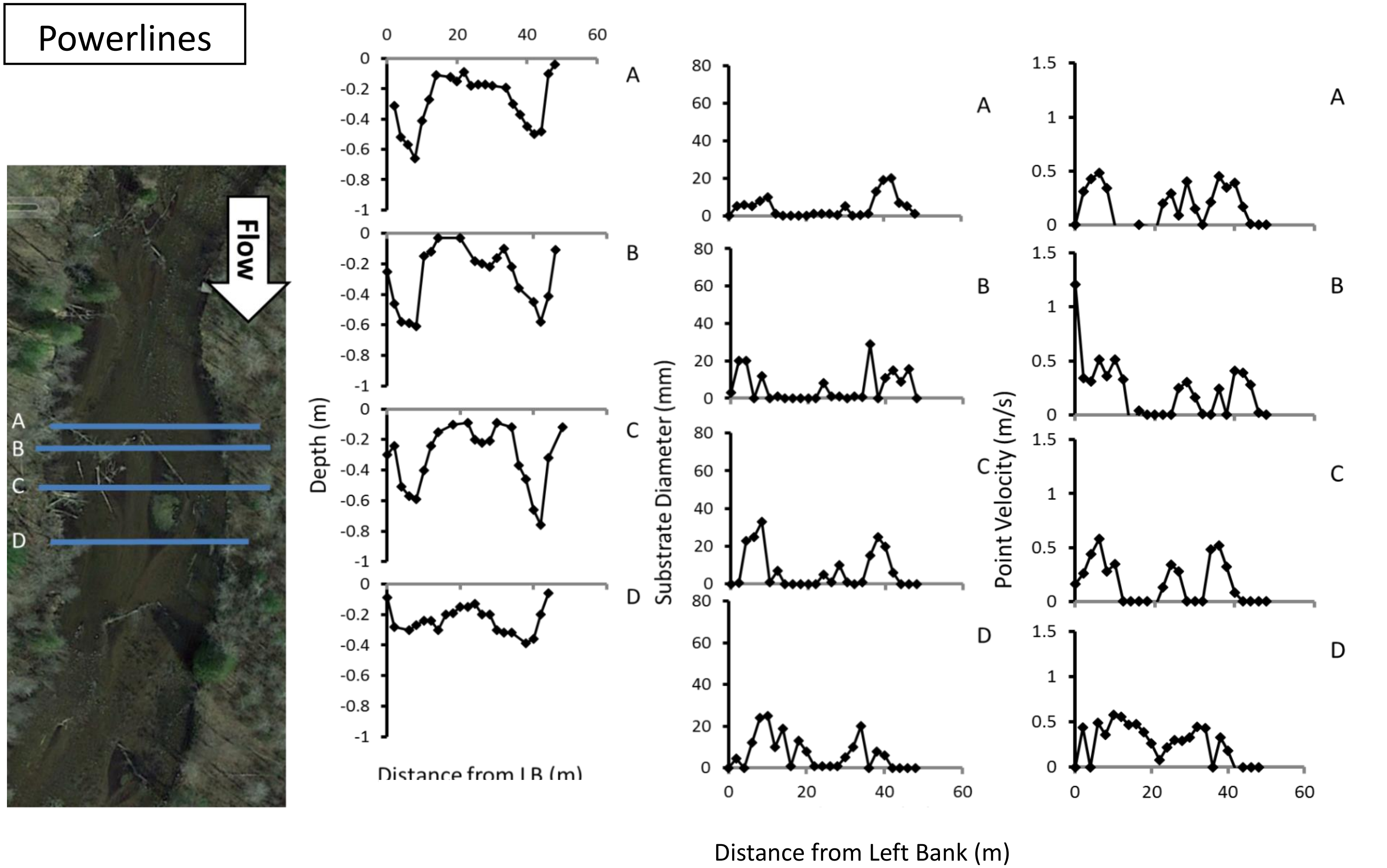

Figure 1.8: Powerlines: Case study of artificial scour structure. Satellite image of Powerlines site (left). Transect measures of depth, velocity, and substrate size in panel of graphs at right. Top row of panel (row 1): graphs labeled A show point data for transect A and so on.

Case Study 3: Twin Bridges Site

The Twin Bridges structure is a deflector-type, which nearly spans the channel width and has substantial flow through it (Figure 1.9). The rationale for installing this structure was likely to create scour, redirect current, and coarsen the substrate. Transect A was located approximately 7 meters upstream of the apex of the structure and did not show a response to the structure's presence (Figure 1.10). Mean depth at this transect was 0.36 m with a standard deviation of 0.13 m. The channel was deeper toward the right bank, but became so gradually. The velocity profile and substrate distribution were largely symmetrical and u-shaped (Figure 1.10). The mean of the velocities at Transect A is 0.29 m/s with a standard deviation was 0.223 m/s. The largest mean particle size occurred near the middle of the channel, the overall mean was 9 mm and standard deviation was 11 mm.

Transect B was located immediately upstream of the structure's apex, and some degree of scour was apparent, with greater depth in the middle of the channel (Figure 1.10, depth pane, row 2). The overall depth and variability of depth at this transect was similar to Transect A (mean = 0.39 m, standard deviation = 0.107 m). The velocity profile for Transect B was roughly D shaped with a mean of 0.32 m/s and a standard deviation of 0.163 m/s (Figure 1.10, velocity panel). There were a few points of slower velocity, which may have contributed to the irregular distribution of sediment sizes (Figure 1.10, substrate panel, row 2); larger particle diameters occurred in multiple channel locations, and smaller maximums of mean pebble diameter than at transects C or E were observed, although the mean (10 mm) and standard deviation (11 mm) were similar to Transect A.

Transect C crossed the center of the structure. Localized scour was evident along each side of the structure (Figure 1.10). Despite having greater maximum depth than the upper two transects, mean depth was slightly less at 0.30 m with similar variability (standard deviation = 0.14 m). The velocity profile for Transect C had two peaks occurring at the channel edges (Figure 1.10, velocity panel, row 3). The mean of the velocities for Transect C was 0.39 m/s $\pm$ 0.24 m/s. Sediment size distribution showed larger particles occurring near the edges of the channel (Figure 1.10, substrate panel, row 3). The mean particle size (13 mm) and standard deviation (14 mm) was slightly larger and more variable than either Transect A or B.

Transect D was located approximately 24 m downstream of the apex of the structure (Figure 1.10). The overall channel profile at this transect was relatively flat, lacking the localized scour apparent in Transect C (Figure 1.10). Mean depth (0.33 m) was similar to other transects, but variability in depth was less (standard deviation = 0.07 m). The velocity profile for Transect D was variable with multiple peaks including areas of slightly higher velocity at the channel edges than in the center (Figure 1.10, velocity panel, row 4). Similar to Transect C, there was an area of sustained lower velocities in the center of the channel (Figure 1.10). The mean velocity for Transect D was 0.44 m/s and the standard deviation was 0.35 m/s. Sediment size distribution was similar to Transect C, with larger average particle diameters occurring near the edges of the channel (Figure 1.10, substrate panel row 4), and slightly greater mean particle size (14 mm) and variability (standard deviation = 16 mm)

Transect E was located approximately 32 m downstream of the structure's apex, outside of the visually apparent influence of the structure when viewed from the ground.

Mean depth at this transect was 0.37 m, similar to Transect A, but was much less variable (standard deviation = 0.06 m). The velocity profile for Transect E was more uniform than Transects B-D (Figure 1.10, velocity panel, row 5). The substrate size distribution and variability were similar to other transects (mean = 11 mm, standard deviation = 11 mm).

As with the Powerlines case study, the effect of this structure on stream habitat conditions was largely in accord with my a priori expectations from the literature.

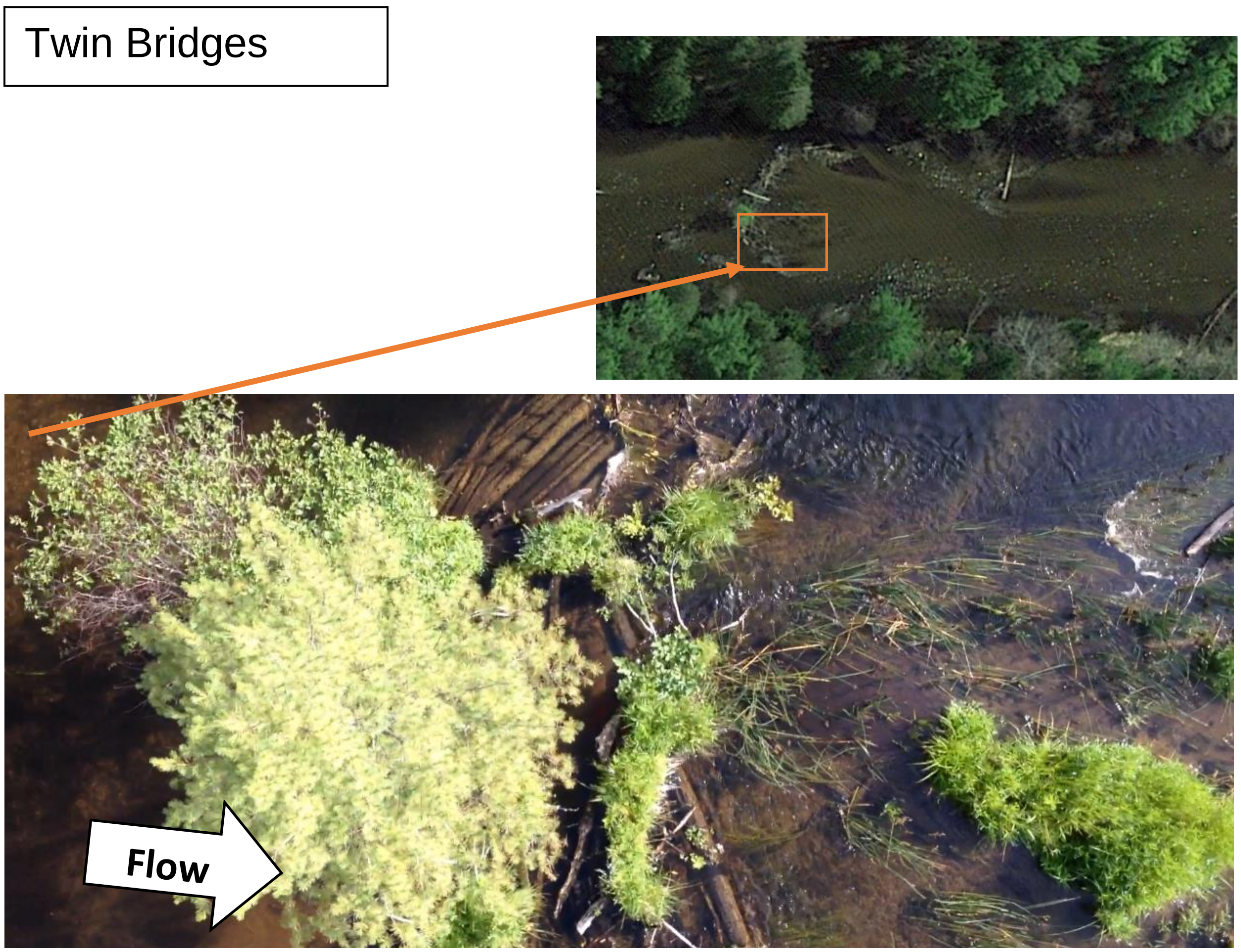

Figure 1.9: Close-aerial photo of Twin Bridges structure, top: satellite image with photo outline

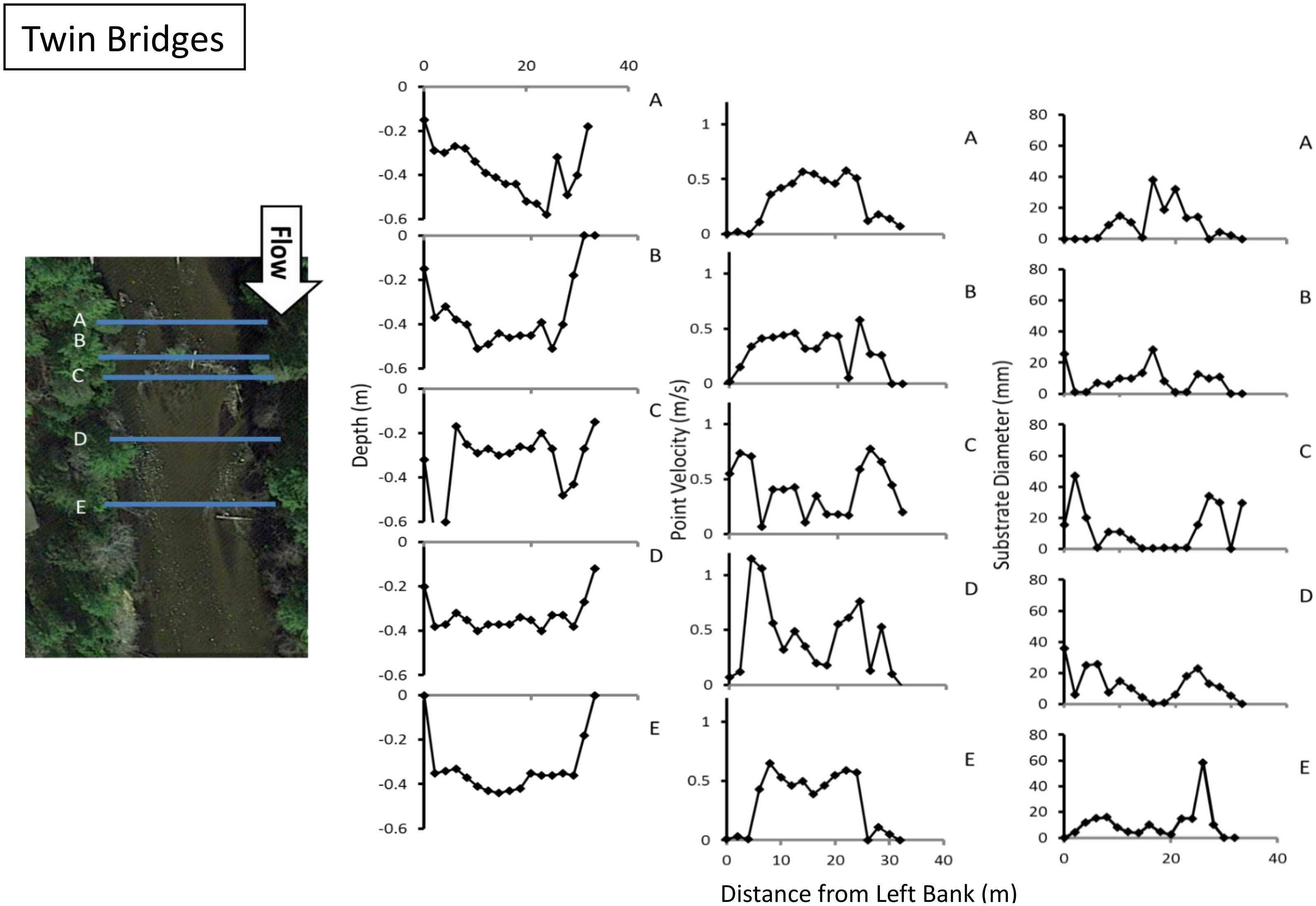

Figure 1.10: Twin Bridges: Case study of artificial scour structure. Satellite image of Twin Bridges site (left). Transect measures of Depth, point velocity, and substrate size in panel of graphs at right. Top row of panel: graphs labeled A show point data for Transect A, and so on.

Case studies indicated that the response of streams to structures was quite localized, and this provided guidance for how data were aggregated across structures. Each case study structure provides examples of the interaction of stream processes. At these structures, and for similar types structures (e.g., case study 2 and 3) the resulting patterns in depth, velocity and substrate are similar.

Aggregated response across structures

Across all longitudinal aggregations, the frequency distribution of depth measurements were unimodal, with a long right tail (Figure 1.11). Transects above the structures had the highest modal depth, followed by transects >10 m downstream of (below) the structures. Modal depths for transects at or within 10 m of structures had the lowest modal depth, but also tended to have the longest right tails, indicative of more heterogeneous depths.

Comparison of the frequency distribution of depths (Figure 1.11) across longitudinal transect categories revealed significant differences (Kolmogorov–Smirnov test ($p < 0.05$)) among all categories except “downstream” and “below,” ($p < 0.07$).

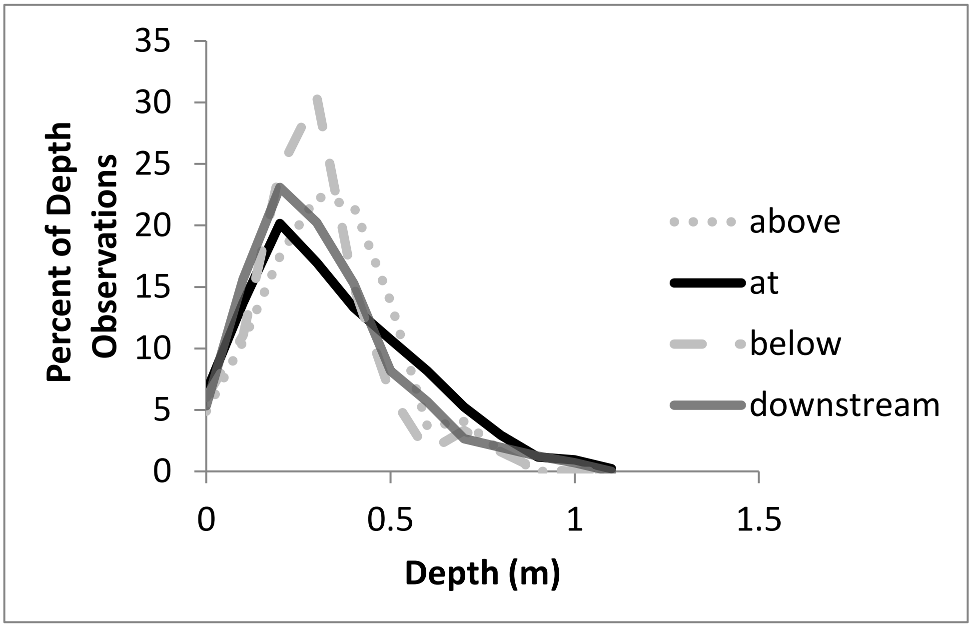

Figure 1.11: Depth frequency by transect type (longitudinal aggregation). Frequencies of depth measurements among survey points located in transects above, at, downstream, or below (>10 m) a structure.

The pattern in the distribution of point velocities depended on the location of transects relative to structures. Transects located outside of the structure influence or below structures but within the influence zone showed a bimodal distribution (Figure 1.12), whereas transects that crossed structures showed a unimodal distribution. The highest frequency of velocities observed at transects located outside the structure influence (far above or more than 20 m downstream) was about 0.3 m/s. In contrast, the most frequently observed velocities for points located in transects at a structure were 0.09 m/s or less, with the majority of observations (53%) being 0.29 m/s or less. As evident in the shape of the distribution (peak of curve closer to 0) of velocities at transects near structures vs. outside or downstream, there was a tendency for point velocities to be lower at transects in the vicinity of structures. Transects at structures were also more likely to feature negative velocities due to turbulent flow or recirculation currents, though these were uncommon.

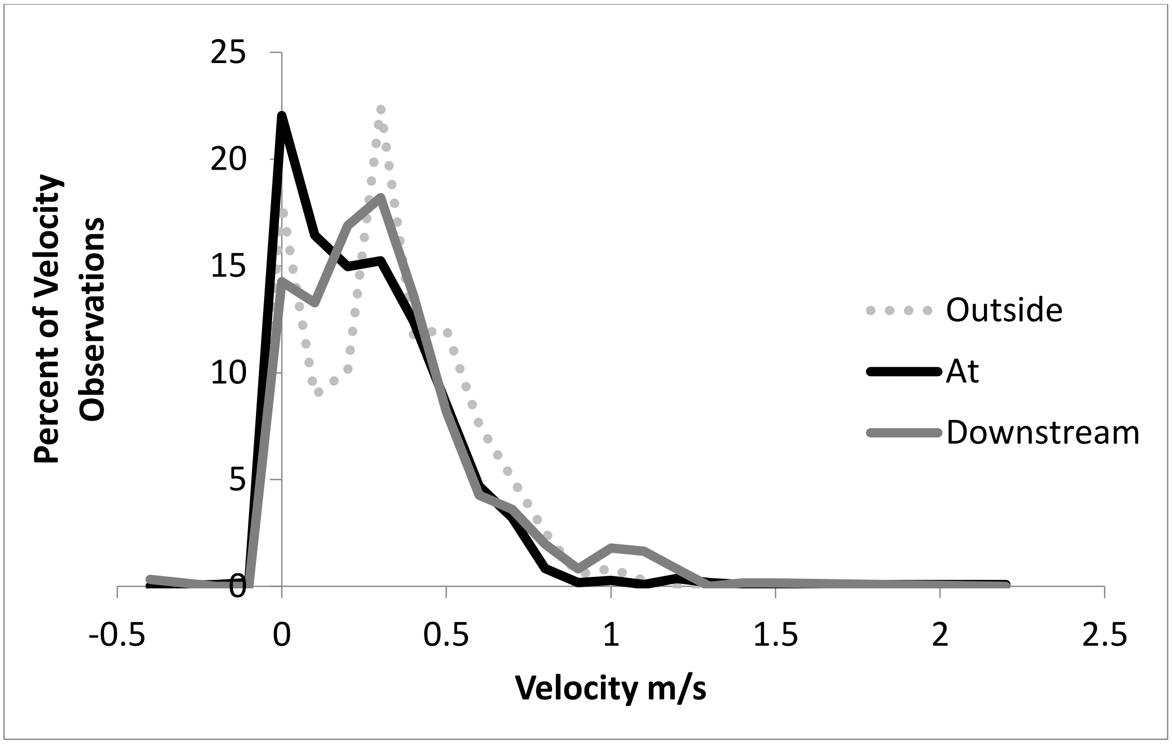

Figure 1.12: Velocity frequency by transect type (longitudinal aggregation). Among survey points located in transects outside, at, and downstream (< 10 m) from structures.

In addition to univariate differences in water depth and velocity distributions among transects, I observed differences in the relationship between these variables associated with transects at, below, and outside the influence of structures (Figure 1.13). Linear regressions showed that in the vicinity of structures ("at" transects), point velocities for a given depth are lower than either those transects farther downstream or outside the structure influence. Transects outside the influence of a structure longitudinally had the highest point velocities for a given depth, and transects below structures, but within the influence zone, were intermediate.

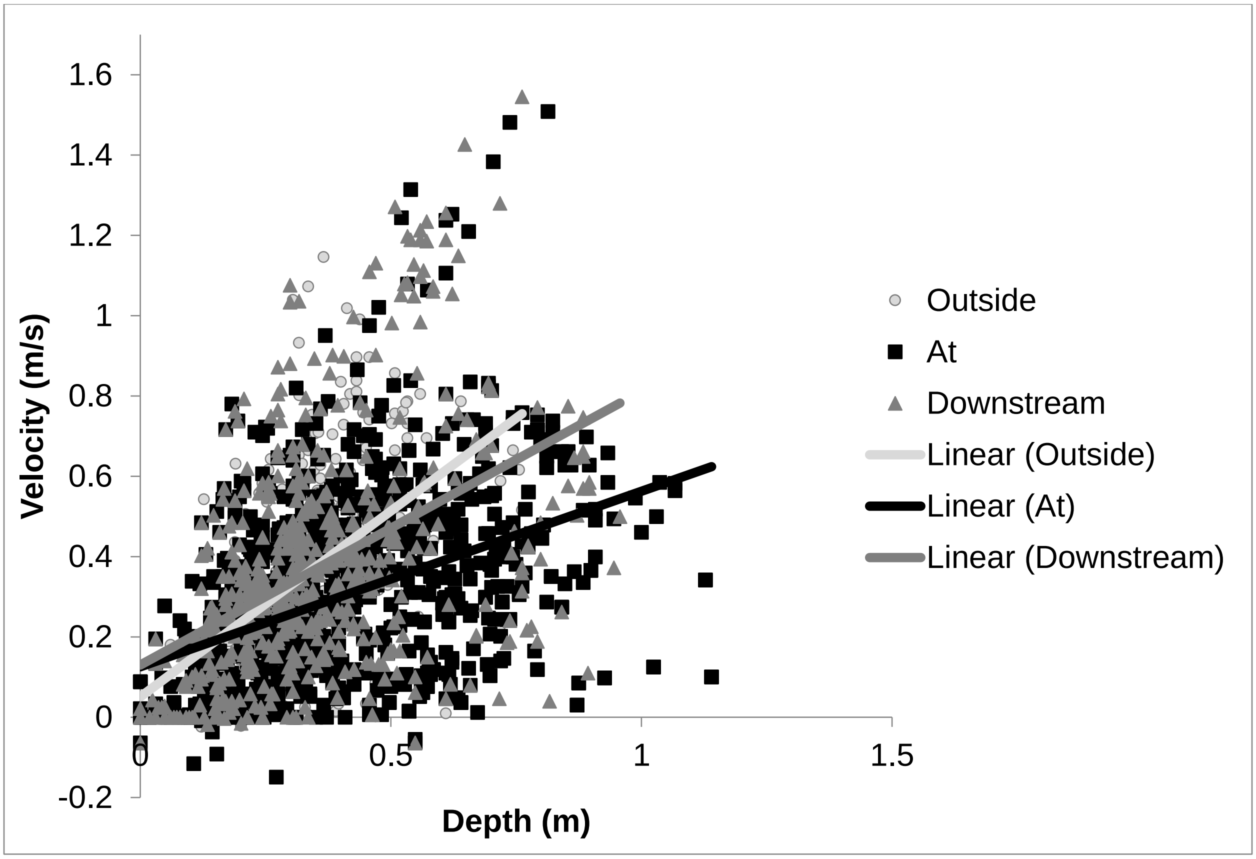

Figure 1.13: Longitudinal aggregate of point velocities compared to depths observed at transects downstream of a structure, at an artificial structure, and outside structure influence.

The North Branch is a system characterized by a mix of sand and gravel substrates. Across all longitudinal aggregations, fine gravel or gravel was the predominant particle size (Figure 1.14). Outside the influence of structures, the substrate distribution featured a high proportion of gravel-sized particles (over 30%). Within those transects closest to structures, coarse substrates were also observed (also over 30% gravel), but transects downstream of structures had smaller size distributions with the highest proportion being fine gravel (Figure 1.14).

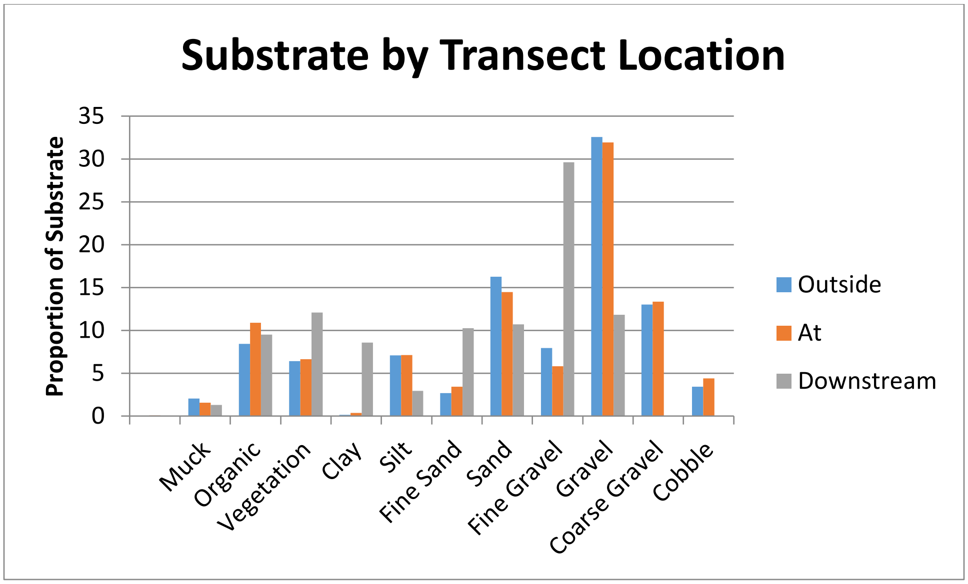

Figure 1.14: Relative frequency of substrate category by transect location. Transect location “outside” refers to transects outside the area influenced by a structure. “At” transects are located within or immediately adjacent to structures. “Downstream” refers to transects in the wake of structures.

In addition to visualizing relationships moving laterally or longitudinally using graphical methods, I created a heat-map style diagram showing the mean point depths (Figure 1.15), velocities (Figure 1.16), and substrate sizes (Figure 1.17) associated with distance bins in relation to a structure. The map shows the small area of increased depth immediately upstream of a structure, and apparent depositional features from 4-20 m downstream. A gradient with depths binned to 0.05 meters, velocities to 0.05 m/s, and substrate particle size in 10 mm increments is included to show the general pattern of scour and deposition associated with structures.

***Depth**(m)* *Lateral distance bin*

Meters longitudinal from structure	*0*	*0.1*	*0.2*
-2	*0.55*	*0.44*	*0.35*
structure	*0.40*	*0.44*	*0.40*
2	*0.30*	*0.33*	*0.31*
6	*0.30*	*0.36*	*0.34*
10	*0.38*	*0.40*	*0.28*
20	*0.28*	*0.36*	*0.40*

Depth (m)

- < 0.35
- 0.35-0.399
- 0.40-0.449
- >0.45

Figure 1.15: Aggregated transect point data for depth (m) associated with structures. Data were binned by lateral distance as tenths of stream width and represented longitudinally. Relationships became less meaningful at distances greater than 0.3 stream widths from the structure.

***Velocity** (m/s)* *Lateral distance bin*

Meters longitudinal from structure	*0*	*0.1*	*0.2*
-2	0.34	0.37	0.27
structure	0.29	0.37	0.35
2	0.43	0.38	0.36
6	0.24	0.39	0.44
10	0.48	0.47	0.41
20	0.26	0.39	0.45

Depth (m)

- < 0.25
- 0.25-0.29
- 0.30-0.349
- 0.35-0.39
- 0.40-0.449
- >0.45

Figure 1.16: Aggregated transect point data for velocity (m/s) associated with structures. Data were binned by lateral distance as tenths of stream width and represented longitudinally. Relationships became less meaningful at distances greater than 0.3 stream widths from the structure.

***Substrate** (mm)* *Lateral distance bin*

Meters longitudinal from structure	*0*	*0.1*	*0.2*
-2	28.0	16.5	17.0
structure	14.0	15.0	12.8
2	17.5	12.0	11.5
6	7.5	14.5	6.5
10	10.5	12.5	7.0
20	10.5	5.0	1.0

Substrate (mm)

- 1.0-9.99
- 10.0-19.99
- 20.0-29.99

Figure 1.17: Aggregated transect data for substrate size (mm) associated with structures. Data were binned by lateral distance as tenths of stream width and represented longitudinally. Relationships became less meaningful at distances greater than 0.3 stream widths from the structure.

Discussion

Structures have been installed in the North Branch and elsewhere to provide cover for fish and alter the physical stream habitat by creating scour in order to increase depth, and substrate particle size. While in-stream structures are prominent in the tool-kit of trout stream managers and practitioners, their effects in a low-power stream system had not been examined as thoroughly as one might expect given how frequently they have been employed. Through close examination of case studies, differences in stream response to individual structures were apparent, particularly in the extent of downstream deposition. For structures overall, aggregate data show how scour in this low-power system was localized and accompanied to varying degrees by swaths of fine sediment deposits. Although structures generally did create some areas of scour, these were often offset by depositional areas. Thus, the patterns I observed in this study were broadly in agreement with predictions summarized in Figure 1.1.

Insights gained from the case studies include differences in stream characteristics associated artificial structures, extent of scour and deposition, and predictability of stream response. The two wing deflectors considered in the case studies showed similar responses in that they both produced a limited extent of scour and created a patchwork of shallow depositional areas downstream of the structure. While practitioners did achieve some amount of scour at each structure, even in the more preferable outcome (Twin Bridges), there was deposition and a substantial portion of the channel was of uniform depth (about 0.4 m). In their immediate vicinity, these structures redistributed the effective stream flow toward the banks leading to higher depth, velocity, and substrate size near the channel edges than in the wake of the structure. The localized areas of coarsening and deepening (scour) were of smaller extent than the area of deposition of fine sediments. Near-bank areas which were coarser were not coarse relative to most standard measures (Wolman 1954) and didn't correlate closely with sediment sizes that practitioners might consider desirable for fish (e.g., for spawning: Raleigh 1982). Further, the increase in areal coverage by sand or finer sediment is likely undesirable for Brook Trout (Alexander and Hansen 1988). Thus, the determination of whether the overall impact of these structures leads to a desirable outcome needs to take into consideration whether that small area of scour is 'worth' the often larger area of deposition.

The Sheep Pasture structure was intended primarily to provide overhead cover. It was associated with localized areas of deeper water and very limited changes to streambed/stream morphology. In contrast to the wing deflectors, there was no substantial depositional feature in the wake of the structure, possibly because it is oriented parallel to flow, is permeable, and easily overtopped at bankfull conditions. If overhead cover had been identified as limiting at this site (which had many areas with undercut banks and a healthy riparian corridor providing shade as shown in Figure 1.5), it probably could have played an important role in increasing overhead cover. In the three case studies above, the most pronounced changes in depth occurred close to the structure itself. The similarity in response in terms of maintenance of deeper water upstream of structures suggests that the scale of impact of individual structures on stream morphology in this river system is relatively localized, on the order of meters to tens of meters.

Developing an understanding of potential tradeoffs requires determining whether the scope of impact observed in the case studies can be generalized across all artificial structures, so I aggregated depth, velocity and substrate particle size data into discrete longitudinal and transverse bins to gain insight into the distance that the effects of the structures propagated downstream, as well as across the stream. Aggregate data for depth compared to longitudinal distance at all transects associated with structures showed the most drastic change in depth occurred within 10 m and diminished further away (Figure 1.15), which is consistent with the case studies. When we consider the band of point measurements downstream centered on the structure's midpoint in the stream, a similar pattern to what we observed in the structures at Twin Bridges and the Powerlines is apparent. Closest to the upstream edge of a structure there is generally an area of deeper water, followed by a wedge where fine particles tend to deposit. The depositional patterns downstream of structures is variable, but fine sands were disproportionately observed in transects downstream of structures, along with gravel of smaller diameter than was observed at, and outside of the influence of structures (Figure 1.14).

Immediately upstream of structures, there tends to be a small (relative to total stream width) area of deeper water (Figure 1.15). Deeper water was followed by moderately deeper areas adjacent and downstream of structures, with shallower water trailing immediately downstream of the structures (areas of deposition). The pairing of localized scour and deposition pose a tradeoff; on the one hand, the development of small areas with faster, deeper water with coarser sediment, and on the other, the potential creation of a wedge of shallower, slower water with fine sediments that can extend 20-30% of the stream width and up to 30 m downstream of the structure.

Structures disrupt flow and create turbulence in their immediate vicinity. Turbulent flow at and within structures creates a disturbance strong enough to reduce the average of aggregated point velocity data for transects "at" the structure compared to transects below or outside the influence of structures. This, combined with the observed changes in sediment and depth near structures, provides further support for the need to balance the interest in creation of additional scour with the potential fluvial repercussions of doing so.

Comparing my findings to expectations from available literature (Figure 1.1)

If managers developed expectations for large effects of artificial structures by considering published literature in higher-power systems (Figure 1.1, cells C and D), they would likely be disappointed by the results observed in my study. The physical forces which dominate stream morphology are different in high and low-power systems. While structures in the North Branch created some areas of deeper water or coarse substrate (Figure1.1, cells A and B), the overall influence of artificial structures on stream depth, substrate size, and velocity, were limited in this low-power system.

As outlined earlier, and featured in numerous warnings in the published literature, stream habitat projects must be fit to the geomorphic and stream process context. Many published studies found varying degrees of stream adjustment, structure durability and overall project success. In this study, there was a lot of variability in the response of the stream to individual structures, and similar variability was observed in the response of fish. While this study had limitations (it was an observational study, with many sites complicated by overlapping structures, or other influences), it does provide valuable insights to the influence of artificial structures on stream morphology in a low-power system. Flow characteristics of this low-power system limit the ability of structures to produce deeper, self-maintaining pools like they might in higher-power systems. The creation of limited areas of deeper water or coarser sediment must be considered in the context of the effort to install and maintain these structures, their aesthetic and recreational impacts, and whether they meaningfully address potential issues with broader stream process and function. These structures are not designed or installed to address stream process and function, and the observed changes to substrate, velocity, and depth are spatially limited, and may not be biologically significant. Therefore, these structures are probably not worthwhile from a management standpoint.

CHAPTER 2:

Response of Brook Trout and Brown Trout to Artificial Structures in the North Branch of the Au Sable River, Michigan

Introduction

River and stream channels have been and continue to be affected by human activity, often leading to impairment of ecosystem function and reduced abundance of valued fish species. Natural resource managers seeking to serve public interests are charged with protecting these resources while expanding fishing opportunities. For example, the Michigan Department of Natural Resources Fisheries Division vision statement includes “To provide world-class freshwater fishing opportunities, supported by healthy aquatic environments, which enhance the quality of life in Michigan” (DNR 2012). In the face of myriad negative anthropogenic effects, management agencies seeking to improve production or abundance of fish have several options. Agencies can stock fish to offset impaired ecosystem functions, change fishing regulations to be protective of existing populations under a degraded habitat condition, attempt to restore ecosystem function through habitat restoration, or a combination of these and other actions. Of these actions, habitat restoration is often favored as this addresses the cause of ecosystem impairment. Where causes of impairment are unknown or difficult to manage, habitat enhancements can make conditions more favorable for species or communities of interest. The installation of artificial habitat structures is a common approach to both restoration and habitat enhancement providing a relatively inexpensive method for addressing specific habitat needs (habitat improvement).

Large-scale projects intended to increase abundance of valued fish started in Midwest streams the 1920s-1930s (Tarzwell 1936). A vast number of habitat structures were installed during this era due to the availability of Federal Emergency Relief Act (FERA) and Emergency Conservation Work (ECW) Act funds (Tarzwell 1935). Early researchers realized, however, that some of these efforts may have been ineffective or misdirected, and advocated the need for evaluation. A particularly pointed quote from that era is:

> "Environmental improvement is a problem of applied ecology. Every lake and stream presents a different problem and its improvement is not so simple as some believe. If we are to improve conditions effectively we must have a knowledge of the habits and know the requirements of the various species which we wish to encourage. Further we must know what necessary factors are lacking or out of balance. We must know how to restore them or put them in their proper relation to other factors necessary for good production. It is therefore apparent that an adequate survey of the waters must be made and experimentation, investigation, and evaluation carried out to determine how the needs must be met."
>
> - Clarence M Tarzwell (1936)

In the intervening years since the era of Tarzwell and others' work, substantial gains have been made in our understanding of the ecology of stream fishes and of the potential effects of artificial habitat structures. Investigations into the effects of artificial habitat structures have been conducted across broad geographic regions, and for decades (Roni et al. 2015a). The importance of cover for fish has long been recognized (e.g., Binns and Eiserman 1979, Boussu 1954, Tarzwell 1936), particularly for salmonids, and has provided much of the impetus for installing artificial structures. A number of physical stream features provide cover, and the prevalence of specific forms of cover is often related to the physiographic region and location along a stream continuum in which the reach of interest is located. As such, artificial structures can be broadly classified as those intended to (1) directly provide cover for fish, and/or those that (2) effect habitat changes by changing stream hydraulics (i.e., scour structures such as current deflectors), leading to more diverse stream conditions (e.g., Hubbs et al. 1932, Hunt 1988, White and Brynildson 1967). Some structures (e.g., rootwads) serve multiple purposes and can be categorized as such (cover and scour simultaneously).

A meta-analysis by Roni et al. (2008) provides a thorough summary of instream habitat improvement, and its effects on biological production in North America, and to a lesser extent Europe. Overall, they found that instream habitat improvement was effective for increasing local fish abundance under many circumstances, but results were highly variable. This variability leads to a continuing perception that some habitat structure installation projects are misguided or ineffective (e.g., Avery et al. 2004; Roni et al. 2015a, Thompson 2002, Thompson 2006). Roni et al. (2008) found that unsuccessful habitat improvement projects often failed to account for the relationship between artificial structures and stream processes, either by not addressing the stream processes most influential to biota or failing to account for the context into which the structures were placed. Further they highlighted that few studies included both physical and biotic effects of artificial structures. Particularly lacking were studies of the impact that artificial structures have on stream channel and habitat characteristics, which was the goal I addressed in Chapter 1; in this chapter I will focus on the response of fish to artificial structures.

Despite cumulative gains in scientific knowledge, much of the research on this topic has been focused on the Western United States, with less emphasis on low-power/low-gradient systems. Because stream processes are dependent on stream power, additional research is needed in low-power systems.

Beyond considerations about stream processes and artificial structure placement, the response of different species and sizes of fish is likely to contribute to the variability in effectiveness observed in studies discussed above. For example, Brown Trout have been shown to orient more strongly to cover structures than Brook Trout (Butler and Hawthorne 1968). Similarly, Whiteway et al. (2010) found Pacific salmonid species and size classes differed in their response to artificial structures. When occurring in the same stream, Brown Trout tend to grow faster than Brook Trout (Carlson et al. 2007), and reach larger sizes (e.g., Carlson et al. 2007, Fausch and White 1981) which was also observed in this study. While both species feed on invertebrates, Brown Trout are more likely to be piscivorous than Brook Trout (e.g., French et al. 2016, Waters 1983, Zimmerman and Vondracek 2007). Further, Brown Trout in sympatry with Brook Trout have also been shown to influence resting positions of Brook Trout to a greater degree than feeding position (Fausch and White 1981), so we could expect the distribution of these species to vary depending on the utility of artificial structures for providing feeding or resting positions.

Given limitations in our current understanding, my goal was to assess the relationship between artificial habitat structure density and density of Brown Trout and Brook Trout in a low gradient stream. My specific objectives were:

A) To determine if Brown Trout and Brook Trout response is different, and how size of fish relates to response.

B) Determine whether fish responded differently to structures intended to provide cover versus those designed to create scour or for other purposes.

C) Identify how stream characteristics (i.e., depth, velocity, temperature) modify the response observed in fish.

Methods

Study Site

My study was located in the North Branch of the Au Sable River in Michigan (Figure 2.1). This section of the Au Sable River is of great interest to natural resource managers and conservation/recreation groups due to its stream characteristics and relatively high density of game fishes. There are several groundwater dominated streams in the Northern portion of Michigan's Lower Peninsula, and while the North Branch is representative of many of these streams due to its physical and biological characteristics, the social, economic and recreational interest, as well as fisheries management history made it an opportune site for this study.

The stream gradient within the North Branch averages 1.34 m/km (7.1 ft/mile; Zorn and Sendek 2001) and ranges from 0.94-3.0 m/km (5-16 ft/mile). The North Branch is classified as a low gradient system by the criteria of Wang et al. (1998). The underlying geology of the watershed of the North Branch is primarily glacial outwash sands and gravels, leading to a stable flow regime (Allan and Castillo 2007) characterized by a high proportion of groundwater. The North Branch and its tributaries drain an area of about 1000 km^2. The stable groundwater supply and cool water temperatures help support resident Brown Trout and Brook Trout populations.

The study included 11 sites, located along a 33 km section of the North Branch (Figure 2.1). Site selection was determined in part by ease of access and sought to include the range of conditions (depth, velocity and temperature), found in the river (Table 1.1). Because of the low gradient and consistent flow characteristic of the North Branch, the range of habitat conditions available was relatively narrow (Table 1.1).

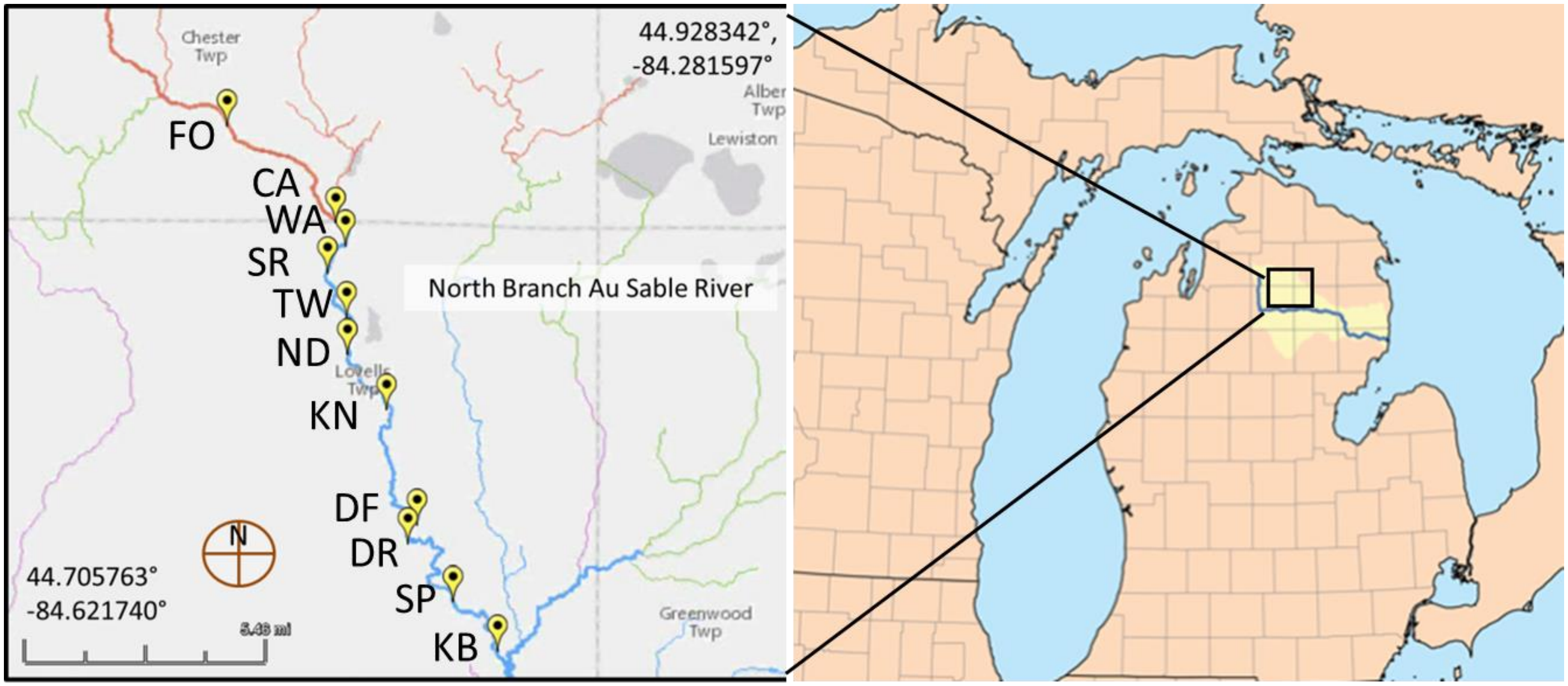

Figure 2.1 Study Sites: Left: North Branch of Au Sable River study area. Sites surveyed in the North Branch are marked with yellow pins and two character site identifiers (KB=Kellogg Bridge access point). The North Branch and its tributaries are colored according to thermal classification (red=warm, blue=cold-transitional, green=warm-transitional, purple=cold) Right: map of Au Sable River watershed (highlighted in yellow).

Fish Sampling

Fish sampling sites averaged 275 m in length, terminating at a point where structures were fully contained within site boundaries. Each site was further divided into sections longitudinally, and subsections laterally, resulting in 246 subsections (Figure 2.2). Sections and subsections were delineated such that where a structure was present, it was contained within one subsection where possible (see upper left of Figure 2.2, where a subsection was expanded to include a tree in the water). In sections where the stream was sufficiently wide (greater than 30 meters), the river was divided in thirds, with two subsections representing "edge" habitat, and one subsection representing the channel center. In narrower sections, less than 30 meters, the stream was separated laterally into two subsections. In each of these cases, care was taken to align divisions such that structures within the stream would be associated with a subsection representing roughly the boundaries of effect of that structure (for example, the pool or depositional area immediately adjacent to a structure, or the area of rough or quiet water in the vicinity of a structure). From these subsections densities of fish and artificial structures were calculated based on section length and mean subsection width (number /m^2). There were a handful of occasions where different configurations were employed, for example at a point where the stream was over 100 meters wide and divided around several islands, either outside channel was its own section, with the middle, larger channel split to be approximately equal size. A few subsections could not be safely electrofished because of deep water or obstacles.

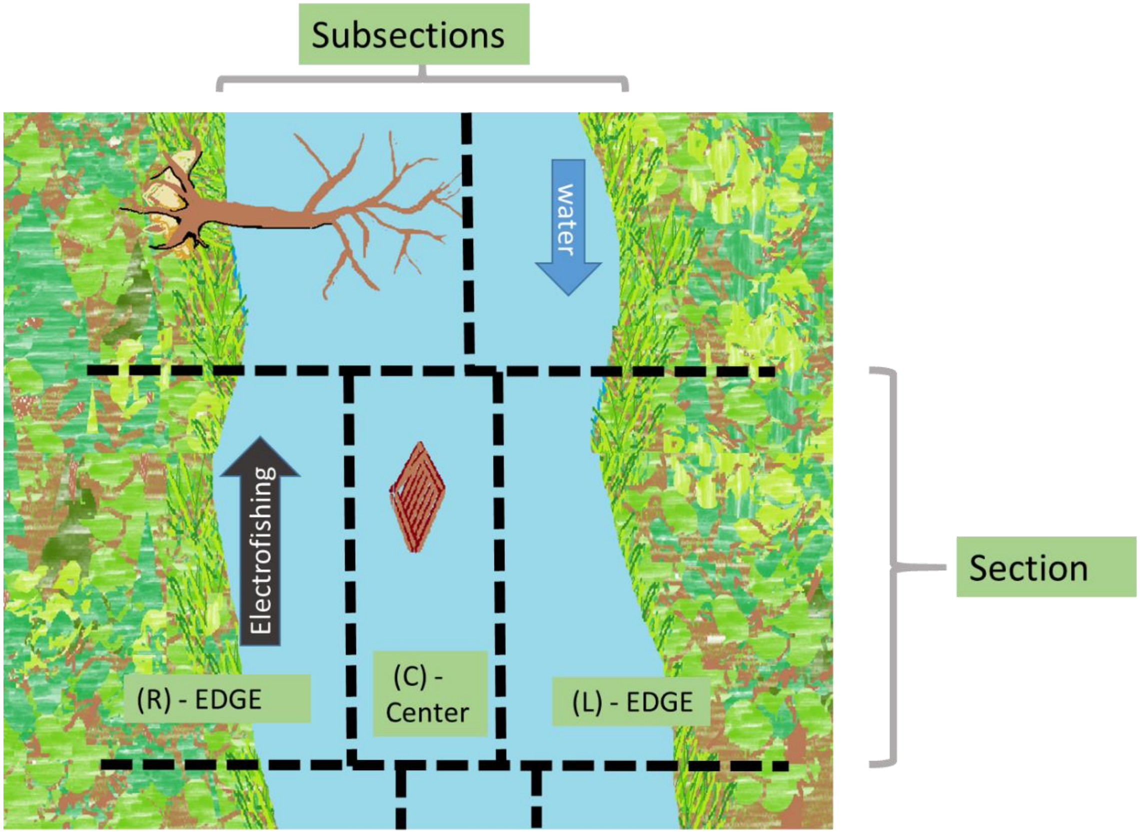

Figure 2.2: Generalized illustration of section and subsection delineation. Rhomboid figure in center subsection represents an artificial habitat structure. Electrofishing effort shown progressing in upstream direction

The fish community at each site was surveyed using a Smith-Root model GPP electrofisher on a tote-barge with two probes (set to 60 pulses per second, DC). In 2014, electrofishing was conducted in July and August, in 2015 electrofishing was conducted in May and June. Electrofishing was conducted in an upstream direction, with fish from each subsection held separately, identified to species, counted, measured and then released. For smaller, more numerous non-game fishes, ~10 individuals per site were measured, and after that counts for each species were recorded. The streams sampled were relatively wide, shallow, and clear. We were often able to observe the behavior of fish in response to our sampling. We rarely observed fish moving beyond the 10 meter width of our sampling path, as such we are confident we were able to capture fish within subsections efficiently.

Data Analysis

The response of fish density to artificial structures was determined by evaluating the density of fish per subsection as a function of the density of structures per subsection, categorized as cover, scour, or multiple purpose structures (Appendix). Further covariates of stream depth, velocity, temperature, substrate, and subsection type (edge or center) were included to evaluate the impact of these contextual variables. Fish density was analyzed separately by species and size groupings to examine the potential for differential response.

For this analysis, Brown Trout and Brook Trout were broken into length classes as different sizes of each species potentially could respond to artificial structures differently (Ayllón et al. 2010, Ficke et al. 2009, Maki-Petäys et al. 1997). In both species, the <100 mm range represented YOY fish. For Brook Trout, the largest individual captured was 310 mm in length, and less than 1 percent of total catch were 300+ mm. As such, Brook Trout were broken into two categories: < 100 mm and >100 mm in length. For Brown Trout, a finer set of size categories was used: YOY < 100 mm; fish older than YOY, but too small to be retained under common angling size restrictions (100-200 mm); fish large enough to be retained under common size restrictions (200-300 mm); and what local biologists consider large fish (300+ mm) (Neal Godby, Michigan DNR, personal communication 2014).

Because the scale of sampling for stream habitat characteristics did not always coincide with section boundaries, there were occasions where some of these means were not available for a particular stream section surveyed for fish. In these instances, the mean for nearby sections or the overall site mean was used. Subsection type in which fish were captured was also included as a variable, with subsections being characterized as either edge habitat or the center part of a stream channel. Dissolved oxygen was also measured, but it was so closely correlated with temperature that it was dropped from the analysis. Moreover, mean oxygen concentration was always greater than 7 mg/L, which is considered to not be limiting to trout (MDEQ 2006).

I explored various analytical approaches including general linear models (GLM), generalized linear models (GENMOD), and generalized linear mixed models (GLIMMIX) using SAS Software (9.3). The fit of the various models was compared through AIC values and evaluation of residuals. Throughout the analysis, I encountered residual distributions that violated model assumptions across a range of modelling efforts including log transforming the data, zero-inflated models, a Poisson error distribution, and a negative binomial distribution with a flexible scaling parameter. Overall, a zero-inflated Poisson regression showed the most reasonable distribution of residuals, but the AICC for this model indicated that increasing the model complexity to account for the zero values in our observational data did not improve the model fit. Having explored a number of alternatives, the Poisson regression as implemented in the SAS GENMOD procedure provided a balance between model complexity and residual patterns. Further, general patterns of results compared across models evaluated indicated that the results were robust to the choice of error distribution.

Results

One of our major objectives was to determine whether there were relationships between fish density and structure type. The relationship between Brown Trout density and the density of multiple purpose structures was non-significant for each size class of Brown Trout (Table 2.1). In contrast, there was generally a significant relationship between the density of Brown Trout greater than 100 mm and the density of cover and scour structures, but not for Brown Trout less than 100 mm. The point estimates for the slope of the regression between fish density and cover and scour structure density were of similar magnitude across size classes. One exception, was a non-significant relationship between density of fish 200-300 mm and scour structure density. The point estimates for this size group had a large standard error and did not fit the pattern observed in adjacent size classes (Table 2.1).

The similarity in point estimates and overlap of confidence intervals for cover and scour regressions led us to evaluate the response of fish to the density of these structures combined (Table 2.2). As above, the relationship between multiple structure density and fish density was non-significant for all size classes. For small Brown Trout (<100 mm), the relationship between combined cover and scour structure density was also non-significant (Table 2.2). For Brown Trout greater than 100 mm, the relationship between combined cover and scour structure density was positive and significant. The estimated slope was similar for 100-200 and 200-300 mm, and the largest size class of Brown Trout (300+ mm) had a higher slope estimate.

For all Brown Trout differences between density in center and edge subsections were negative, indicating that edge habitats are associated with higher densities of

Brown Trout (Table 2.2), but differences were significant only for the smallest and largest size classes. The density of Brown Trout <100 mm in length was significantly negatively related to mean depth and mean temperature (Table 2.2), and significantly positively related to mean velocity (Table 2.2). For Brown Trout >100 mm in length, the only significant relationships observed for the other habitat variables were a positive relationship between mean water velocity and the density of Brown Trout in the 100-200 and 200-300 mm groups (Table 2.2).

Brown Trout		<100 mm			100-200 mm			200-300 mm			300+ mm		
		esti-mate	standard error	Pr > Chi Sq	esti-mate	standard error	Pr > Chi Sq	esti-mate	standard error	Pr > Chi Sq	esti-mate	standard error	Pr > Chi Sq
Artificial Habitat Structure Density	Cover	-20.24	14.09	0.15	32.94*	8.80	0.0002	40.72*	10.07	<.0001	50.10*	9.29	<.0001
	Scour	-31.18	29.47	0.29	36.30*	12.36	0.0033	-11.69	26.67	0.66	43.21*	14.78	0.0035
	Multiple	4.34	29.57	0.88	11.52	26.23	0.66	33.95	26.42	0.20	4.21	35.65	0.91
Stream Habitat Variable	Center-edge	-1.57*	0.42	0.0002	-0.46	0.24	0.06	-0.50	0.33	0.13	-1.76*	0.52	0.0006
	Depth	-0.86*	0.40	0.03	0.25	0.34	0.47	0.54	0.42	0.20	0.34	0.41	0.41
	Velocity	0.77*	0.18	<.0001	0.73*	0.16	<.0001	0.66*	0.20	0.0013	0.24	0.22	0.29
	Temperature	-0.35*	0.08	<.0001	0.01	0.06	0.90	-0.03	0.08	0.71	-0.02	0.08	0.78

Table 2.1: Response of Brown Trout density to artificial habitat structures and stream habitat characteristics. Significant relationships are marked with an *. Artificial structures were categorized by intended function: cover structures, scour-producing structures, or structures with multiple intended purposes. Point estimates are the slope of the regression line between the number of artificial structures, or the stream habitat measure, and fish density, except for the center-edge estimate, which is the mean difference in density between subsections characterized as center subsections and those characterized as edge subsections.

Brown Trout		<100 mm			100-200 mm			200-300 mm			300+ mm		
		esti-mate	standard error	Pr > Chi Sq	esti-mate	standard error	Pr > Chi Sq	esti-mate	standard error	Pr > Chi Sq	esti-mate	standard error	Pr > Chi Sq
Artificial Habitat Structure Density	Cover+ Scour	-22.31	12.92	0.08	34.02*	7.32	<.0001	30.88*	9.46	0.0011	48.10*	7.97	<.0001
	Multiple	4.76	29.45	0.87	11.16	26.17	0.67	37.78	26.04	0.15	5.52	35.28	0.88
Stream Habitat Variable	Center-edge	-1.57*	0.42	0.0002	-0.46	0.24	0.06	-0.57	0.33	0.08	-1.77*	0.51	0.0006
	Depth	-0.85*	0.40	0.03	0.25	0.34	0.47	0.59	0.42	0.16	0.33	0.41	0.42
	Velocity	0.77*	0.17	<.0001	0.73*	0.15	<.0001	0.62*	0.20	0.0024	0.24	0.22	0.29
	Temperature	-0.35*	0.08	<.0001	0.01	0.06	0.88	-0.05	0.08	0.57	-0.03	0.08	0.74

Table 2.2: Response of Brown Trout density to recategorized artificial habitat structures and stream habitat characteristics Significant relationships are marked with an *. Artificial structures were re-categorized: cover structures combined with scour-producing structures, and structures with multiple intended purposes. Point estimates are the slope of the regression line between the number of artificial structures, or the stream habitat measure, and fish density, except for the center-edge estimate, which is the mean difference in density between subsections characterized as center subsections and those characterized as edge subsections.

Similar to Brown Trout, the slope of the regression between Brook Trout density and multiple purpose structure density was not significant across both size classes (Table 2.3). For small Brook Trout (<100 mm) none of the estimates of the effects of structures were significant (Table 2.3). The relationship between Brook Trout >100 mm density and cover structure density was significant and positive (Table 2.3), whereas the relationship for scour structure density was non-significant. The confidence interval for slope did not overlap between scour and cover structure density so the distinction was retained.

The density of Brook Trout <100 mm and >100 mm responded similarly to all environmental variables examined (Table 2.3). Density was significantly higher in stream edge subsections, and declined with water depth, and increased with water velocity (Table 2.3). The relationship of Brook Trout density to water temperature was small and not significant (Table 2.3) for both size classes.

Brook Trout		<100 mm			>100 mm		
		estimate	standard error	Pr > Chi Sq	estimate	standard error	Pr > Chi Sq
Artificial Habitat Structure Density	Cover	-7.43	12.71	0.56	25.12*	8.46	0.003
	Scour	-51.41	31.67	0.10	-17.96	20.20	0.37
	Multiple	-24.03	37.08	0.52	-68.18	44.74	0.13
Stream Habitat Variable	Center-edge	-1.27*	0.37	0.001	-0.85*	0.26	0.001
	Depth	-1.87*	0.44	<.0001	-2.26*	0.37	<.0001
	Velocity	0.74*	0.18	<.0001	0.82*	0.16	<.0001
	Temperature	-0.08	0.07	0.23	0.035	0.05	0.52

Table 2.3: Response of Brook Trout density to artificial habitat structure type and stream habitat characteristics. Significant results marked with an *. Artificial structures were categorized by intended function: cover structures, scour-producing structures, or structures with multiple intended purposes. Point estimates are the slope of the regression line between the number of artificial structures, or of the stream habitat measure, and fish density except for the center-edge estimate, which is the mean difference in density between subsections characterized as center subsections, and those characterized as edge subsections.

Even for significant relationships between density of structures and fish density, univariate graphs of these relationships show a great amount of variability (Figures 2.3-2.5). These results highlight the fact that even where the relationship between trout density and structure density is positive, there are other environmental factors that influence trout density, and there remains considerable variability in the response of trout to these structures.

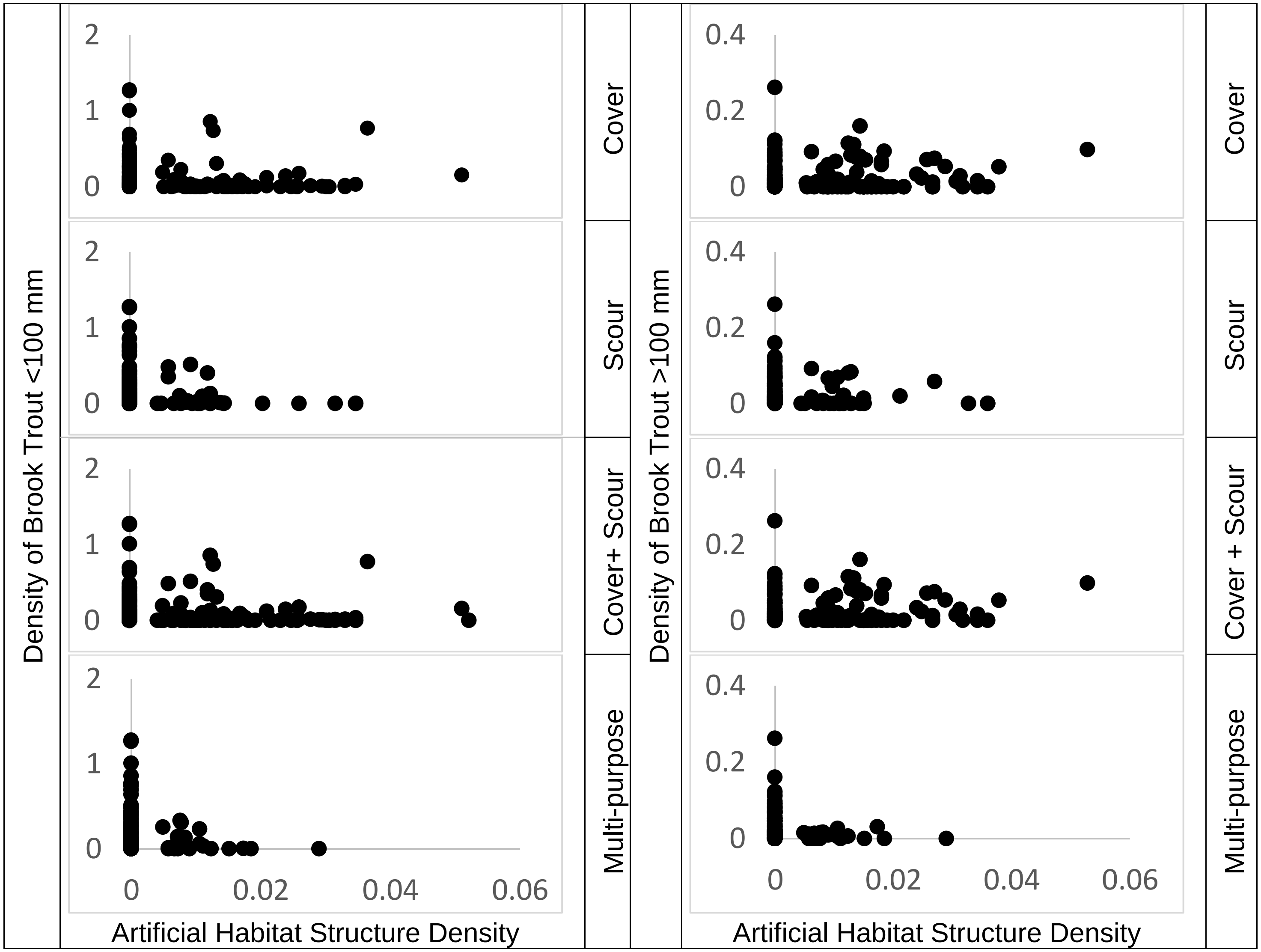

Figure 2.3: Relationship between Brook Trout density and the density of artificial habitat structures.

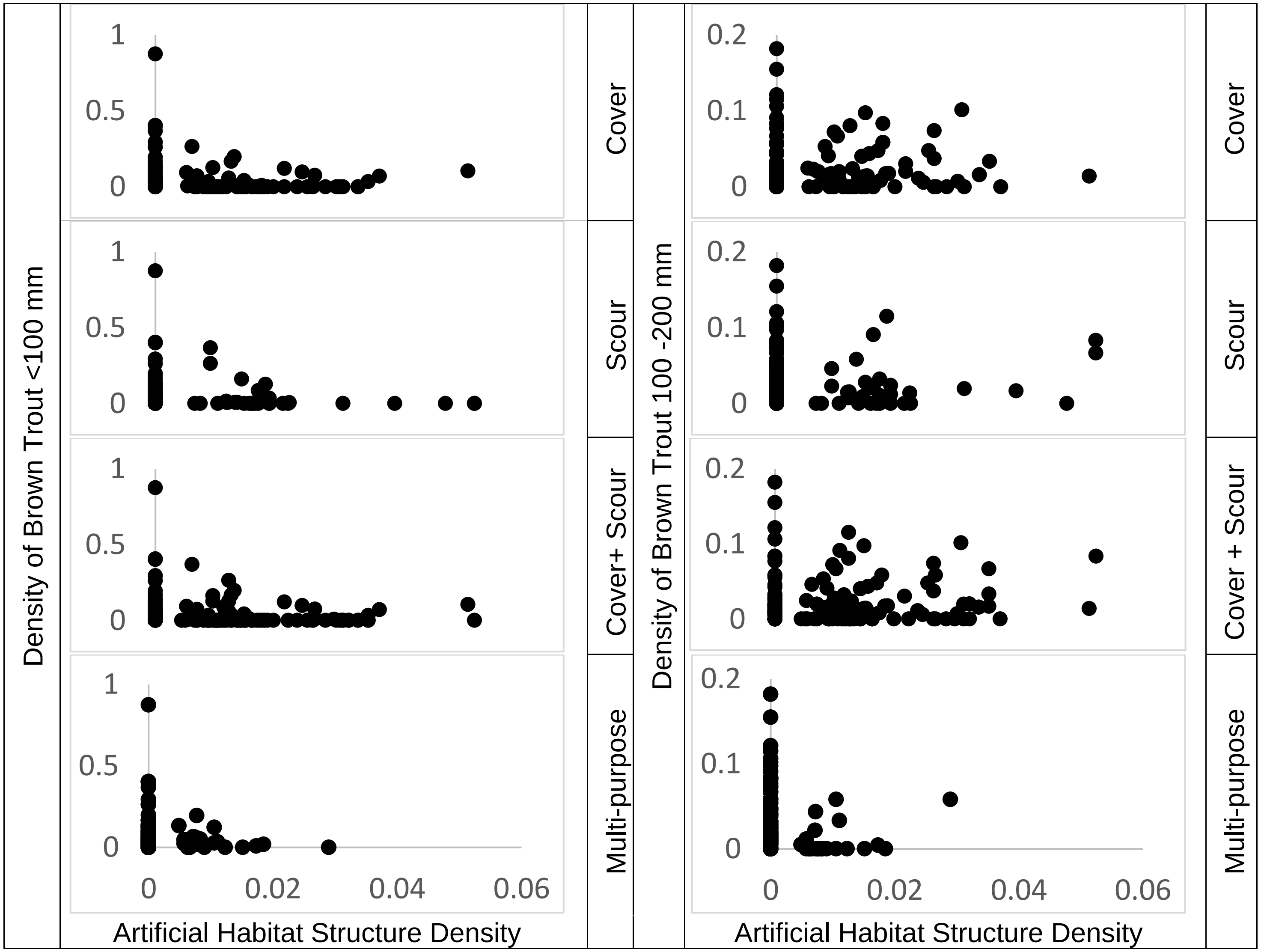

Figure 2.4: Relationship between density of Brown Trout <100 mm, and 100-200 mm in length and the density of artificial habitat structures.

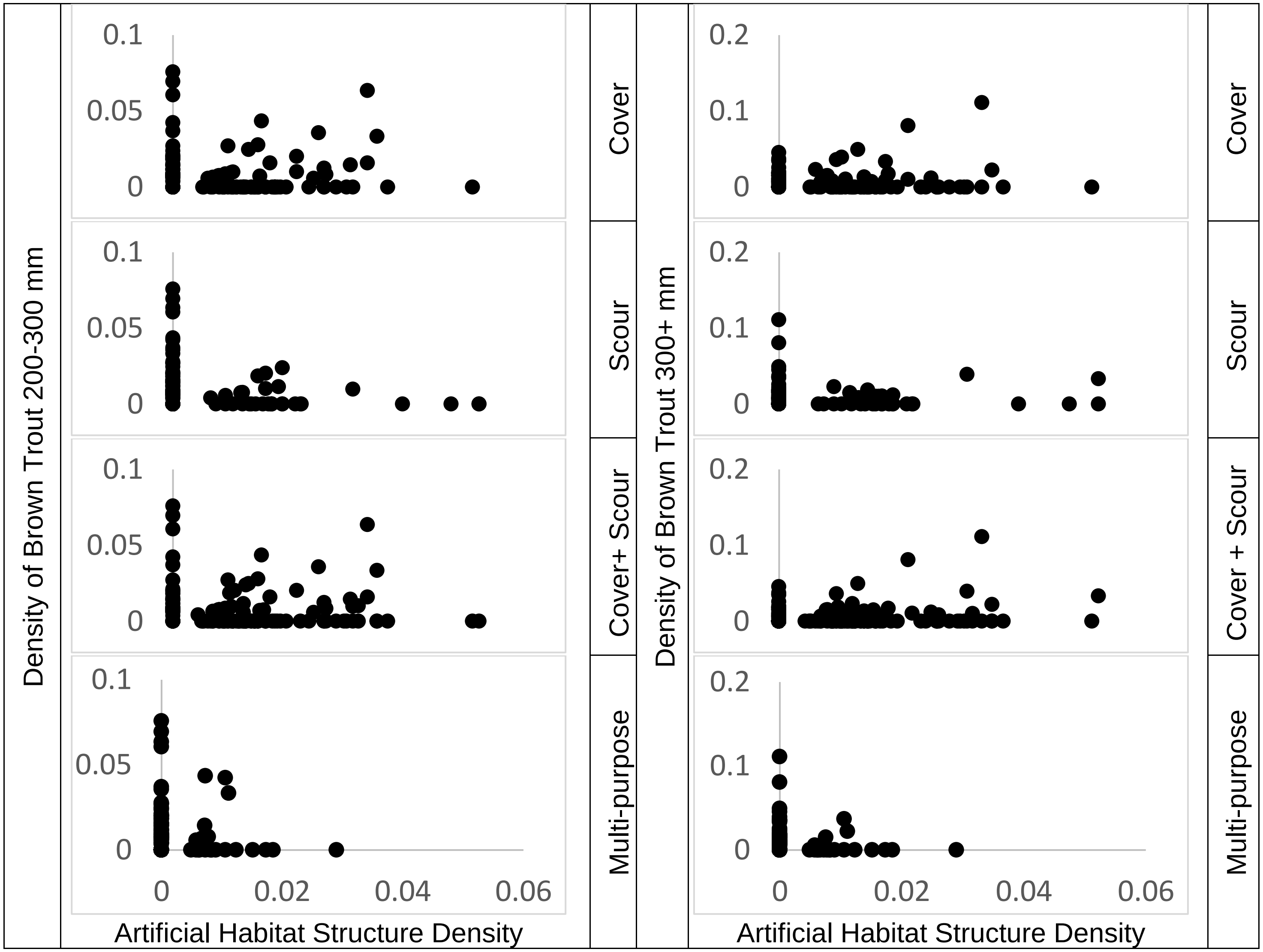

Figure 2.5: Relationship between density of Brown Trout 200-300 and 300+ mm in length and the density of artificial habitat structure

Discussion

Natural resource managers in both the public and private sectors have often been motivated to conduct ‘active’ management by direct alteration of physical habitat in order to increase the density of valued game fish such as trout. While other methods have also been employed (e.g., bank stabilization, work on road-stream crossings) here I focus on in-stream structures, because of their prominence in the tool-kit of trout stream managers. One of the challenges identified in Roni et al. (2015) is the wide variability in responses of fish and stream habitat to artificial structures in general. As such my *a priori* expectation was that the response of fish density to structures would vary as a function of structure type, fish size and species.

Overall, Brown Trout density showed a positive, significant association with density of artificial cover and scour structures, but no relationship was observed for multiple purpose structures. The slope of the regression was similar for both cover and scour structures leading me to conduct a combined analysis, treating these as equivalent in their effect on Brown Trout density. The response of small Brown Trout (<100 mm) was non-significant, but I observed a progressive increase in the slope across larger size classes.

Brook Trout showed a contrasting response to artificial structure density. Similar to Brown Trout, the relationship between cover and scour structures and Brook Trout less than 100 mm was non-significant, and the relationship to multiple purpose structures was non-significant. However, density of Brook Trout greater than 100 mm showed a varying response to cover types. Brook Trout density showed a strong response to cover structure density, but not to scour structure density. The implication of this is the choice of structure type appears to be more important for Brook Trout than Brown Trout. The contrasting response to structures by Brown Trout and Brook Trout was also observed by Avery (2004).

In a review of 58 projects, Avery (2004) found that allopatric populations of Brown Trout and Brook Trout responded similarly to instream structure additions, but that in sympatric populations, Brown Trout responded much more positively than Brook Trout. Avery (2004) found that installation of deflector structures (which are a subset of scour structures) lead to an increase in trout mean size and biomass, and in 75% of projects examined, a 25% or greater increase in density was observed. Although my study's design differed from Avery (2004), my finding of that the strongest response was for the largest Brown Trout size class is consistent with his finding of increased mean trout size.

My findings are broadly consistent with meta-analysis and similar review papers (e.g., Avery 2004, Roni et al. 2013, 2015a) which showed a trend of higher fish density where structures have been installed, and in areas with more structures. My findings are also consistent with the literature (e.g., Roni et al. 2008; Smokorowski and Pratt 2006) in that this trend occurs within a tremendous amount of variation. The univariate graphs demonstrate the substantial variability in trout density under observed ranges of cover and scour structure densities (Figures 3-5). Some of this variation is due to the influence of stream habitat characteristics, of which I measured depth, velocity, and substrate.

As shown in Chapter 1, among all structure types examined, there tended to be a small area of deeper water in the immediate vicinity of a structure (generally within 2 meters), and many structures were associated with finer substrates in the downstream area, sometimes on the order of tens of meters. As shown in the case studies, the area of deposition varied widely. It is possible that some of the variability observed in densities of Brown Trout and Brook Trout was due to the balance of the competing effects of artificial structures. Further, the response of these species likely also depended on the conditions of the reach in which artificial structures were placed.

Brown Trout and Brook Trout density showed differing relationships to the covariates I examined. Brown Trout <100 mm showed a significant response to all variables examined, whereas Brown Trout >100 mm appeared to primarily respond to velocity. Brook Trout < 100 mm also had significant responses to all covariates, except temperature, but Brook Trout >100 mm also responded to these variables in a significant manner. This highlights the importance of considering the context of the stream as well as structure type and target species when an artificial structure project is implemented. In addition, seasonality may change the range of habitat conditions, particularly water temperature, fish encounter. Thus, the response of Brook Trout and Brown Trout may differ seasonally, I did not focus on seasonality in this study.

In addition to the variability due to stream habitat characteristics, a further source of variability is the possibility that choice and placement of structures may not have been appropriate to the context of the stream. Roni et al. (2015a) made a similar observation emphasizing the importance of matching habitat improvement projects involving wood placement to an appropriate geomorphic setting.

Management Implications

The advice of Tarzwell (1936) rings as true today as it did then. Although the density of trout, particularly Brown Trout, was higher in areas with more artificial structures, the considerable variability indicates that factors other than those addressed by the structures also limit trout abundance and distribution. Diagnosing which factors are limiting, and importantly, which can be addressed through management manipulation remains a major challenge outside the scope of this study. For example, results from this study indicate that edge sections consistently held higher densities of Brook Trout as well as some size classes of Brown Trout, therefore it seems likely that maintaining the health of the riparian corridor is an important goal. As another example, some sections of the North Branch are warmer than optimal for the support of robust trout populations. As such, adding structure to these sections would not be expected to offset stream temperature as a limiting factor. As I document in Chapter 1, the scale of impact of individual artificial structures is typically localized (i.e., on the order of meters to tens of meters), and typically do not reduce stream width. Without changes to width, and with localized deepening of the channel, overall velocity profiles would be expected to decrease for a given flow since the overall cross-sectional area would tend to be maintained or even increased. For stream sections with a suite of conditions indicative of impairment (e.g., overly wide, shallow, fine substrate) practices such as applying Natural Channel Design, restoration of stream functions, including competence and capacity, controlling accelerated erosion of sediment from uplands, or work to alter flow through human infrastructure such as bridges or culverts may be needed.

Even where limiting factors can be identified, an important consideration is the choice of restoration approach. If physical manipulations are to be employed, careful consideration of what tools are available is necessary. My discussion here focuses on the subset of tools represented by various types of artificial habitat structures. In areas where depth and velocity distributions are suitable for trout, but where cover is limiting, the natural choice would be to install cover structures that would be expected to have minimal scour impacts. Examples of such structures include bank covers, especially to replace sea walls or to promote regrowth of riparian vegetation. Where depth and velocity distributions are limiting (i.e., low-power systems represented in cells A and B of the matrix in Chapter 1, Figure 1.1, including rivers like the North Branch which has many sections that are wide, shallow, and of low velocity), structures that are designed to modify the cross-sectional area of the stream and restore stream function would be a better choice than a cover structure.

When methods are being explored to modify stream channel characteristics, I recommend that more strategic and wide-reaching physical modifications to the stream pattern and profile may need to be considered, particularly in low-power streams like the North Branch. One approach which is increasingly popular among state and federal agencies is Natural Channel Design a system developed by Rosgen (1994). Natural Channel Design includes fluvial geomorphological assessment and emphasizes the need for a thorough understanding of stream dynamics and processes prior to conducting any work. Rosgen cautions that designs are likely to under-perform or fail without appropriate assessment and stream data incorporated in their development

(Rosgen 2007). While useful, Natural Channel Design requires an understanding and project scope beyond the scale of individual artificial structures.

Rosgen is one of many stream experts advocating the need to account for, address, and maintain or restore stream processes (sediment, water quality, connectivity, etc.) prior to or in conjunction with instream habitat projects (Roni et al. 2002, Roni et al. 2008, Roni and Beechie 2013). For example, before employing a large woody debris project to restore a system, it is critical to confirm a paucity of large wood is the major factor that needs to be addressed (Roni et al. 2015a). Failure to employ restoration or improvement techniques that are appropriate for the stream system was considered a major factor in studies which showed no response in terms of physical habitat or a decrease in the biological factor of interest (i.e., salmonid abundance) (Roni and Beechie 2013).

As I have shown, artificial habitat structures can be a useful component of a broader restoration or habitat improvement strategy but identifying how and what to install requires an understanding of stream processes that are critical to overall project success. Because stream processes occur at a watershed scale, depending on the resources and expertise of the practitioner seeking to improve stream habitat for the benefit of fish, collaborating with others may be necessary to achieve project goals.

APPENDIX

Intent	
Cover	Protection from predators, provide resting areas
Scour	Maintain coarse substrates
	Increase depth
	Increase habitat heterogeneity
	Flow refugia
	Promote deposition
	Vegetation growth
	Reach or watershed level sediment transport
Infrastructure or human benefit	Docks
	Bridges
	Culverts
	Dams
Location	
Lateral	Mid-channel
	Bank (edge)
Vertical	Surface
	Partially submerged
	Submerged/in water column)
	Embedded
Construction	
Materials	Natural (whole trees, branches)
	Semi-natural (logs, slabs, boards)
Engineering	None (materials free to drift)
	Moderate (limited ability to move)
	High (use of nails, cables, rebar etc.)
	Extreme (mimics effect of dam, channelization, which effects 1/3rd or more of bankfull channel)

Table 2.4: Characteristics of Artificial Structures. Intent, location and construction of artificial structures. Summarizes terms used for classifying intended function of artificial structures in streams.

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