Fish response to velocity-related habitat modification in a warm water stream

by

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AMDG,

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Abstract

Recent developments in the field of stream restoration have led to multiple strategies for improving and restoring a variety of fish habitats across spatial and geographical scales. These habitat modifications often aim to increase overall fish abundance or species diversity through the installation of in-stream structures. Historically these structures were common in cold water streams for improvement of salmonid habitats, but as stream restoration projects are needed in smaller and warm water streams it is important to understand and quantify the effects of in-stream structures on other fishes. Velocity is thought to be an important parameter in determining fish habitat choices and hence essential for successful restoration of aquatic ecosystems. This project attempted to change velocity profiles using in-stream structures and determine if these changes attracted fishes. In this project solid blocks were installed perpendicular to the primary flow direction at ten sites located in runs and riffles in a warm water stream in Northern Michigan in order to create velocities similar to those experienced by fishes in pool habitats. The modified sites and two pools were surveyed by snorkeling over a one-month period to determine fish use of the newly created habitats. The physical flow conditions were measured using an Acoustic Doppler Velocimeter and a Marsh-McBirney flow meter.

Fishes did not utilize the artificially created habitats despite large reductions of local velocity behind the blocks. Current speeds behind the blocks were actually lower than those measured in pools and in some cases were opposite in direction to the main channel current. Pools and modified sites showed significant differences in mean velocity, velocity fluctuations, turbulent kinetic energy, and turbulence intensity. Velocity gradients which developed at the edges of the blocks may have been a barrier to fish access to the modified sites, since they were much larger than those occurring in natural pools. Results suggest that several physical characteristics of flow patterns are crucial in describing the complexity of fish habitats and that velocity alone does not provide enough information to determine the suitability of an area for fishes.

Introduction

Aquatic ecosystems of all types have been decreasing in area and species diversity for most of the past century (Palmer et al. 2010). Because human populations and industries tend to congregate around rivers and streams, fluvial ecosystems have been particularly impacted. In recent decades interest in restoring these systems to their former function has increased greatly (Roni et al. 2005). Historically, river restoration efforts were focused on bank stabilization, but many recent projects involve the creation or improvement of fish habitat using installed in-stream structures (Thompson 2006). Most habitat improvements and structure installations have been directed at salmonids (Quinn and Kwak 2000) because of their economic importance in the fisheries and tourism industries (Botsford et al. 1997). Many large game fishes are concentrated in cold-water habitats and therefore most work to date has been performed in cold-water streams. With increasing interest in stream restoration and rehabilitation over a wider geographical and ecological range of habitats, (Bernhardt et al. 2005), smaller and warmer reaches are now being targeted for improvement projects. An increase in fish diversity or abundance may provide socioeconomic benefits, is often desirable from a management perspective, and may be selected as a metric of improvement (Wills et al. 2004). In order to achieve these goals, engineers and resource managers need a better understanding of the biological and physical parameters non-salmonid fishes positively respond to, as well as how to construct, restore and maintain these habitats.

The use of man-made fish attracting structures has been met with mixed results, and there is currently no overall consensus in the literature as to whether or not these projects truly work. For example, Binns (2004) analyzed 30 river habitat improvement projects, including the use of in-stream structures, done by the Wyoming Fish and Game department between 1970 and 2000 and found that most projects increased trout abundance and biomass. In contrast, Stewart et al. (2009) performed a review of 132 published journal articles on the use of in-stream structures and found that the current scientific evidence does not support their use for fish habitat restoration. In-stream modification projects have been most successful where the stream catchment around them (at the scale of square kilometers) has been minimally disturbed by human-driven changes in land use and water quality (Wang et al. 2006). Where habitat modifications have not worked as intended, their failure has been attributed to being too small-scale (Rosi-Marshall et al. 2006), having too little structural complexity (Angermeier and Karr 1984, Smokorowski and Pratt 2007) or having poor project planning and design (Kondolf et al. 1996).

This experiment studied the relationship of velocity with fish habitat choice between modified and unmodified areas. The hypothesis was that creating areas of low velocity in riffles and runs of a warm water stream would allow fishes to use them as feeding and resting habitat (Lobb and Orth, 1991, Bowen et al. 1998). This would increase fish abundance in riffles and runs by providing suitable habitat where previously velocities were too high for fishes to remain for long periods.

Materials and Methods

Experimental Outline

This experiment sought to create areas where the velocity range was similar to that of pools in the runs and riffles of a warm water stream in order to increase suitable habitats for fishes to rest and feed. It involved comparison of four different site types: reference sites, sites modified by the installation of one block, sites modified by the installation of three blocks, and comparison pools (Figure 1). Reference sites and modified sites are both found in runs and riffles and were selected in order to cover the range of current speeds, substrates and depths found in the study area. The purpose of reference sites was to account for fish use of unmodified riffle habitat over the course of the study; if fishes began to appear in riffles more frequently as a result of population increase or migration as opposed to using the modified habitat, reference sites would be a way to evaluate this pattern. The purpose of comparison pool sites was to compare velocity and velocity-related characteristics to those of the modified sites. The goal was to make modified sites similar to pools based on velocity metrics, since pools are a choice habitat for fishes.

Study Area

Observations were made on 250 m of the East Branch of the Maple River in Pellston, MI (T37N, R4W, S25) in June, July, and August 2009 (Figures 2 and 3). This warm water stream originates at Douglas Lake and contains groundwater inputs as well as surface runoff (Zorn et al. 2002). The pool-run-riffle sequence is partially constructed by large woody debris creating logjams located on average every 50 m of stream length. The substrate consists of sand and gravel. Land cover around the study area is deciduous forest consisting primarily of American beech (*Fagus grandifolia*) and quaking aspen (*Populus tremuloides*).

Initial Survey

An initial survey of possible sites for modifications was conducted June 25th-30th, 2009. Current speed, water depth, and substrate composition were measured at 15 sites spanning the range of these characteristics which appeared throughout the study reach. Sites were marked in the stream and on the banks using numbered flags, and only sites which were expected to maintain a low flow depth of greater than 10 cm were selected. The placement of site markers away from banks and obstructions such as large woody debris or boulders ensured that current speed and velocity measurements were representative of the reach as a whole. Current speed (U) averaged over 5 seconds was measured at 60% of total depth from the surface using a Marsh-McBirney electromagnetic flow meter (Hach, Colorado, U.S.A.). Depth was measured using a meter stick. The coverage of the bottom by sand and gravel was estimated visually to the nearest 10%. The presence of vegetation and woody debris were also recorded (Table 1).

The distribution of fishes along the 250 m stretch of the Maple River was recorded on two separate trips on July 8th and 13th, 2009 using snorkel surveys proceeding from the downstream end of the study reach and working upstream. Fishes were counted in this survey if they were within one square meter downstream of the center of the site marker or block. Fishes were identified to species. Abundance was estimated and recorded for five classes from no fishes to more than 20 (Table 2). Abundance classes were chosen to recognize the log-normal shape of species abundance curves, in which most species are expected to have few representatives and a few species have large numbers of individuals. Two pools in which fishes were abundant were selected to serve as comparison pools during these snorkel surveys. Current speed, depth, substrate composition, and presence of vegetation and woody debris were measured and recorded in the same manner as described above.

Habitat Modification Evaluation

The purpose of the habitat modifications was to create low velocity refuges in runs and riffles with velocities similar to those found in pools. First, two pools in which fishes were always seen were selected for comparison of velocity and velocity-related characteristics to the modified sites in runs and riffles. Second, five sites spanning a range of velocities and substrate compositions in runs and riffles were selected as reference sites (Table 1). Reference site locations were selected to be representative of typical local velocity conditions in the natural stream and to provide a point of comparison for changes in fish abundance and flow patterns at the reach level. Third, ten sites also spanning the range of velocities and substrate compositions in runs and riffles were modified with the addition of a single 8” x 8” x 16” (20.3 cm x 20.3 cm x 40.6 cm) concrete block oriented with the longest dimension normal to the primary flow direction with a solid side facing up and downstream (Figure 1). All blocks were emergent, except Site 14, located in a run. Lastly, after nine days, five of these one-block sites were further modified with the addition of two more blocks across the flow. The purpose of widening the site modifications was to increase the size of low-velocity areas behind the modifications and potentially make them easier for fishes moving through the stream to find and use.

Current speeds (U) in the reference sites and modified sites were initially measured using a Marsh-McBirney flow meter in order to rapidly assess the baseline conditions as well as the effect of modifications. Current speeds were also measured at non-modified comparison pool sites where fish were frequently seen in order to roughly estimate the range of current speeds in these areas. At reference sites current speeds were measured at the four corners and center of one square meter with the site marker located at the center in order to adequately represent the local conditions of the reference site. For the modified sites, current speed was measured at 10 cm intervals for 50 cm in the x (streamwise) direction and 5 cm intervals over 200 cm in the y (cross-stream) direction from the geometric center of the block (Figures 4, 6, and 8). After nine days, five sites were widened with two additional blocks and Marsh-McBirney measurements were repeated at all ten modified sites. The coordinate system used to mark the measurements had the positive directions being downstream and to the left when looking downstream. Current speeds in pools were measured in the center, at the edges and in a line from the inlet to the outlet at 30 cm intervals.

Since the Marsh-McBirney only provides overall current speed information, detailed velocity measurements were made with a Nortek Acoustic Doppler Velocimeter (ADV) (NortekUSA, Maryland, U.S.A.) for a representative one-block site, a three-block site, and a comparison pool. The ADV measured velocity at a single point in the x (streamwise), y (cross-stream), and z (vertical) directions (U_x, U_y and U_z respectively) at a frequency of 25 Hz for 120 seconds. A sampling period of two minutes was selected in order to measure a representative amount of flow variation which would not be affected by turbulent processes on the time scale of a few seconds (Nikora 2007). This sampling period has been shown to be sufficient for steady open-channel flows (Chanson et al. 2007). All ADV measurements were collected using a sampling volume located 4 cm from the stream bottom, which was a representative depth where fish were usually seen. In the natural pool, velocity was measured at the center and at left and right edges. Behind the one-block and three-block structures, measurements were taken at multiple locations in the cross-stream direction 10 centimeters downstream of the structure, similar to the procedure used with the Marsh-McBirney. Additional ADV measurements were taken directly behind the left and right edges of the block where turbulent eddies were visible on the water surface (Figures 5, 7, 8, and 9). In the comparison pool ADV measurements were taken in the same locations as Marsh-McBirney measurements: in the center, at the edges and in a line from the inlet to the outlet at 30 cm intervals.

Measurement Errors in ADV Data

All collected ADV data include information on signal-to-noise ratio (SNR) and correlation values. SNR and correlation values indicate the quality and accuracy of ADV data and as such should meet minimum standards before being used for analysis. For this experiment all SNR values were above 15 dB and all correlation values were required to be above 70%, consistent with suggested practical thresholds for ADV analysis (Chanson 2008).

Other possible sources of error in ADV measurements include insufficient particles in the flow and boundary effects if the ADV sensor is placed too close to a solid surface (Mueller et al. 2007). There was sufficient natural particle concentration in the water column and no seeding of the flow was necessary. Boundary effects were assumed negligible as the sampling bottom was located 4 cm from the stream bed. This assumption is supported by the strong correlation values (averages were above 90%) and SNR values (average was approximately 30 dB). Finally, experimenters were stationed on the banks during data collection so as not to create flow disturbances.

Fishes

Fish distributions were first surveyed after site selection had been completed and all fifteen sites were marked as described above. Two snorkel surveys of all fifteen sites and comparison pools were done five days apart (8 and 13 July 2009). Following the first set of habitat modification, all sites were surveyed twice in a seven-day period (24 July and 1 August 2009). After extending five of these sites to include three blocks, all fifteen sites were surveyed two more times in a three-day period (2 August and 4 August 2009). For modified sites, fishes were counted if they were seen within one square meter downstream of the center of the block configuration. The same abundance classes and surveying patterns were used as in the initial survey.

Calculations

ADV data were analyzed using Explore V and Microsoft Excel. Five metrics were selected to study the flow characteristics using velocity and its derivatives in the studied habitats. Average resultant velocity is a common metric for determining habitat suitability for fishes (Vogel 1996). In order to find the average, the resultant velocity (U_{Ri}) was first calculated for each measurement according to the following equation:

$$U_{Ri} = \sqrt{{U_{xi}}^2 + {U_{yi}}^2 + {U_{zi}}^2} \tag{1}$$

U_{xi}, U_{yi} and U_{zi} are individual instantaneous velocities in the x (streamwise), y (cross-stream), and z (vertical) directions, respectively. The average resultant velocity $\overline{U_R}$ over the entire sampling period at a single point in space is:

$$\overline{U_R} = \frac{\sum_{i=1}^{n} U_{Ri}}{n} \tag{2}$$

where n is the number of samples in the sampling period. The velocity standard deviation and variance are statistical measures of the velocity distribution. When applied to the average resultant velocity $\overline{U_R}$ they indicate how much the velocity varies around the calculated mean. A small standard deviation implies low velocity fluctuation over the sampling period. The equation for standard deviation is:

$$\sigma_{\overline{U_R}} = \sqrt{\frac{(U_{R1}-\overline{U_R})^2+(U_{R2}-\overline{U_R})^2+...+(U_{Rn}-\overline{U_R})^2}{n}} \tag{3}$$

where n is the number of samples in the sampling period. The variance of $\overline{U_R}$ is:

$$Var = {\sigma_{\overline{U_R}}}^2 \tag{4}$$

Another important parameter is Turbulent Kinetic Energy (TKE). TKE quantifies energy associated with deviations from the mean velocity, so high TKE values are indicative of turbulent flow fluctuations. These variations affect fish control and are important in the design of fish-related structures (Tsikata et al. 2009). The equation for turbulent kinetic energy at a given time in the sample is:

$$TKE_i = (U_{xi} - \overline{U_x})^2 + \ (U_{yi} - \overline{U_y})^2 + (U_{zi} - \overline{U_z})^2 \tag{5}$$

where $\overline{U}$ is the average velocity in the given direction over the entire sampling period and U_i is the velocity measurement in the same direction at a given time. TKE was averaged over the 2-minute sample according to the following equation:

$$\overline{TKE} = \frac{\sum_{i=1}^{n} TKEi}{n} \tag{6}$$

Finally, responses of fishes to flow conditions are more likely to be affected by how these variations relate to physical attributes of the flow. This is apparent in the calculation of turbulence intensity (TI), which scales the variation of a velocity measurement by its average velocity. Highly turbulent flows may be easier for fishes to navigate when they are accompanied by the significant momentum of a fast-moving current. The calculation of TI relies on the standard deviation of $\overline{U_R}$ ($\sigma_{\overline{U_R}}$), and the average resultant $\overline{U_R}$, both of which are calculated using all collected data at a single point. Therefore TI has only one value for each sampling period.

$$TI = \frac{\sigma_{UR}}{\overline{U_R}} \tag{7}$$

Results

Stream Habitats

The East Branch of the Maple River was comprised of pools, runs, and riffles (Webb 2006). One of the pools spanned the stream width of 3 m, and ranged in depth from 0 cm at the shoreline to 60 cm at the deepest point in the middle. The second pool was created within the flow by large woody debris, spanning 1.5 m of the stream and ranged in depth from 10 to 15 cm at the edges to 30 cm at its deepest point. Five-second time-averaged speeds (measured with the Marsh-McBirney) at 60% of the depth from the surface and in the center of the pools where fishes were found ranged from 7 to 17 $cm.s^{-1}$. Pools contained shoals of fishes from 10 to more than 20 individuals (abundance classes 4 and 5; Table 2). The most common species was hornyhead chub (*Nocomis biggutatus* Kirtland) with smaller numbers (in order of decreasing abundance) of creek chub (*Semotilus atromaculatus* Mitchell), common shiner (*Notropis cornatus* Mitchell), yellow perch (*Perca flavescens* Mitchell), and Iowa Darter (*Etheostoma exile* Girard).

Runs ranged in depth from 16 to 34 cm, with current speeds from 10 to 45 $cm.s^{-1}$. Runs contained hornyhead chub, creek chub, and common shiner in abundances in classes 2 and 3 (Table 2). Riffles were the shallowest of stream habitats with depths from 15 to 28 cm and current speeds of 25 to 69 $cm.s^{-1}$. The same species of fishes as in runs were seen but in very small numbers, in abundance classes 0 and 1.

On the basis of the survey of the stream reach sampled, fishes were most abundant in pools, at the edges of the stream near the banks and on the outside edge of meanders. Most natural pools, including those selected for comparison with modified sites, consistently served as resting and feeding habitat for upwards of twenty individuals at one time. Presence of large woody debris also appeared to be positively correlated with fish sightings, as fishes were often seen hovering below and just downstream of logjams. Few fishes were seen in riffles and races, and became less common in these habitats as water levels in the stream dropped over the course of the summer. When fishes were seen in riffles, they were actively moving through the area as opposed to resting or feeding, and they were rarely seen in groups larger than five individuals.

General Flow Patterns at Reference Pools and Block-Modified Habitats

The habitat modifications sought to create low velocity refuges in riffles and runs with current speeds similar to those found in pools. Flow speeds measured after modifications were somewhat similar to those in pools, but they were smaller in range and included more negative values than pre-modification measurements. In spite of increasing the size of some modifications from one to three blocks, similar ranges of total current speeds and negative speeds were found for both the one-block and three-block configurations at each site. Therefore the size of modification changed only the size of the area where the flow speeds were modified, not the flow patterns observed.

Five-second time-averaged current speeds recorded using the Marsh-McBirney were used to quantify general flow patterns in the comparison pools and at the various sites, both before and after modifications. For the two comparison pools, current speeds ranged from 7 to 17 cm.s^{-1} in the deeper center areas where fishes were seen, but the range was 0 to 54 cm.s^{-1} over the entire pool (Figure 9). Current speeds at experimental sites were reduced with the insertion of blocks (Table 3). Sites in runs had an average pre-modification current speed of 29 cm.s^{-1} and sites in riffles had an average pre-modification current speed of 54 cm.s^{-1}. Pre-modification current speeds in riffles and runs are within the range measured in the pool, but far fewer fishes were counted in riffles and runs during the initial survey than in pools. Following the insertion of blocks at the modified sites, the current speeds 5 cm behind the center of the one- or three-block configurations were in the range of -4 to +2 cm.s^{-1} (Table 3). This is a greatly decreased range of current speeds, in spite of a seven-fold variation at the sites prior to the addition of blocks, as well as almost entirely negative. The insertion of blocks also generated areas of visibly higher velocity, caused by the block edges, which had disappeared at a distance of 100 cm downstream (Figures 4, 6, and 8). For an area spanning the width of the blocks across the stream and approximately a meter downstream, current speeds ranged from -4 to 27 cm.s^{-1} (Figure 8), which is a much larger range of speeds than those found in the preferred location of pools. Furthermore, when the entire region of the flow affected by the blocks is considered, current speeds varied from -7 to 74 cm.s^{-1}. This greatly exceeds the range of current speeds measured in the pools.

However, there were larger differences in the flow patterns between the pools and modified sites than apparent in the mean flow data. A very noticeable feature of the modified sites was the inclusion of negative velocity values within the 25th percentile of values (Figure 10), whereas no negative speeds were found in pools. The creation of areas of negative velocity was an unintended consequence of modification and may have had a major impact on the usefulness of these habitats for fishes.

Detailed Flow Characteristics at Reference Pools and Block-Modified Habitats

Following completion of the measurement of general flow patterns, ADV measurements were taken at four sites and one comparison pool to obtain more detailed information on flow characteristics, specifically average resultant velocity, standard deviation, variance, TKE, and TI values at each data point. Due to changes in discharge over the time period of the experiment and the differing precision levels of the instruments, the numerical data for the Marsh-McBirney and ADV were not equivalent. To preserve this separation they were not combined in the data analysis; statistical analysis was done using Marsh-McBirney data only (Table 6), as was the creation of box plots (Figure 10). Contour maps for TI were drawn based on ADV data while those for velocity were drawn with Marsh-McBirney data, but the two measurements do not appear in the same map.

Fishes would be expected to choose sites where they are less likely to be destabilized by large velocity variations (Smith 2003). In this experiment, this would be where standard deviation in velocity measurements tended to be lower. Standard deviations in the mean resultant velocity, σ_{U_R}, varied within sites and among sites (Table 5). For the comparison pool the velocity varied most at the center, with a standard deviation of 3.46 $cm.s^{-1}$ in the middle of the pool compared to 2.85 $cm.s^{-1}$ at the pool edge. The same was true for the unmodified riffle site; velocity variations were larger at the center of the site (3.58 $cm.s^{-1}$) than at the edge of the site which was closer to the banks (2.57 $cm.s^{-1}$). These values were similar in magnitude despite being located in different types of microhabitats (a pool as opposed to a riffle). However, once the block was added to the riffle site, with the goal of creating velocity conditions more similar to those in pools, the standard deviations changed in both magnitude and location. When the blocks were added to the riffle site, the standard deviation at the site edge more than doubled

(6.66 cm.s^{-1} with blocks compared to 2.57 cm.s^{-1} without), which made it higher than the standard deviation measured behind the block, which was reduced by more than 50% (1.23 cm.s^{-1} compared to 3.58 cm.s^{-1} without). This was a large change in magnitude of standard deviation values and it was very different from the values measured in the pool, which were more similar to the values measured without the blocks than with them. Furthermore, the addition of the blocks shifted the location of higher velocity variation towards the banks and away from the thalweg, where it had been located before modification.

Mean velocity $\overline{U_R}$ followed the same pattern as σ_{U_R}, in that it varied most at the center of both the pool and the unmodified site, but in the modified site it varied most at the edges and dropped significantly behind the block. Before modification, site 34 had an average velocity ranging from 13.33 cm.s^{-1} at its edge to 14.97 cm.s^{-1} in the center (Table 5). This was comparable to the velocities measured in the pool where fish were seen (10.08 cm.s^{-1} at the edge to 10.41cm.s^{-1} in the center). Once the block was added to site 34 the edge velocity became close to that of the pool (10.79 cm.s^{-1}) but the velocity behind the block dropped to 3.08 cm.s^{-1}, a decrease of 380% from the unmodified velocity. This modified velocity of 3.08 cm.s^{-1} was lower by approximately 4 cm.s^{-1} than was ever measured in the center of pool habitat where fish were seen. This suggests that the block edges created a flow environment which fish might have found useful, but, when the previous findings on standard deviations are considered, the flows would have been much more varied around modified sites than in a pool environment, which would likely have negative effects on fishes' attempts to maintain stability.

Flow patterns differed spatially between pools and downstream of the blocks. First, the location of low velocity areas was different between the pools and modified sites. Low velocity values and gradual gradients were measured at pool edges, while the edges of the blocks were characterized by high velocity gradients. Starting at a point near the center of Comparison Pool #1 to a point near the pool edge, the velocity decreased from 18.0 to 6.0 cm.s^{-1} over 100 cm, for a gradient of 0.12 (cm.s^{-1}).cm^{-1} (Figure 9). From the center of the same pool to the pool outlet the gradient was 18.0 to 14.0 cm.s^{-1} over roughly the same distance, giving a gradient of 0.04 (cm.s^{-1}).cm^{-1}. In contrast, for the right side of a three-block site (Figure 4), the flow speed changed from -1.0 cm.s^{-1} to 11.0 cm.s^{-1} over a distance of 15 cm, a gradient of 0.8 (cm.s^{-1}).cm^{-1}.

This gradient was larger in the three-block configuration than the single block, and it was 560% larger than the largest gradient measured in the pool habitat. At the same site with a single block (Figure 4) this change of flow speed did not occur until 20 cm beyond the edge of the block. The transition is from -1.0 $cm.s^{-1}$ to 8.0 $cm.s^{-1}$, over 20 cm, a more gradual gradient of 0.45 $(cm.s^{-1}).cm^{-1}$, which is still 275% larger than the highest gradient measured in a pool. This suggests that the edge gradient was increased by extending the structure farther across the flow. In addition, the large velocity gradients, also areas of high shear, were areas of eddy formation.

Turbulent kinetic energy associated with velocity variations, and hence the energy that could create displacements of the body for fishes or overwhelm their stability (Tarrade et al. 2006, Lupandin 2005), is proportional to velocity fluctuations^2 (Equation 5). TKE had average values of around 25.0 $cm^2.s^{-2}$ at both the edges and center of pool habitats (Table 5). In contrast, site 34 showed large variations in TKE both before and after modification. The center of the unmodified site had a TKE value of 145.0 $cm^2.s^{-2}$, which was much larger than the value closer to the bank of 15.13 $cm^2.s^{-2}$. After the block was installed, TKE at the center dropped to 5.48 $cm^2.s^{-2}$, while at the edge it increased to 79.58 $cm^2.s^{-2}$. The large difference at the center location made sense because the presence of the blocks decreased the average velocity, but there were still turbulence patterns present in the flow. Interestingly, the edge of the block has a lower velocity than the same location before modification, but much higher TKE values. This correlates with the previously discussed pattern of larger standard deviations in the same location, and suggests that in this area the flow is more energetic and could cause stability and swimming challenges for fishes.

While variations in velocity do impact fish habitat choices (Smith 2003, Enders 2003), the momentum of the system may facilitate damping of displacements associated with velocity variations, such that fishes in faster flows could handle larger velocity variations. This idea is encapsulated in TI, which was calculated as the ratio between the standard deviation of the mean resultant velocity,σ_{U_R}, and the mean resultant velocity $\overline{U_R}$ (Equation 7). TI in the center of the pool was 0.33 and at the edge it was 0.28. These values are somewhat higher than those in the riffle, which had values of 0.19 at the edge and 0.24 at the center. However, the addition of blocks greatly increased the TI values measured in the riffle, to 0.60 at the edges, and 0.40 behind the block, which were increases of 215% and 66% respectively from pre-modification values. These values were higher than those found in either of the pools, and further study of TI values measured at modified sites showed that the pattern of differences in TI between pools and modified habitats was repeated throughout the experiment.

Contour maps of TI were drawn for three representative modified sites (Figures 5, 7, and 8). A riffle site had a maximum TI value behind the block of 2, which was five times larger than the value in the main channel of 0.4. The turbulence intensity was consistently higher behind the center of the blocks than in the center of the pool (Figures 4 and 6). The center of the comparison pool had TI values from 0.3 in the center to 1 near the pool edges where water was nearly stagnant (Figure 9). This is an example of increased TI values behind blocks that were much higher than those found in the main channel and comparison pools. Main channel turbulence intensity was measured at maximum values of 2.0 in riffles and 0.65 in runs, which was consistent with observations that these sites were not preferred by fishes before modification; their turbulence intensity values may have been too high for fishes to maintain stability.

Finally, with respect to the structures added to the flow, site 14 was previously mentioned as being submerged. This differed from the rest of the modified sites, whose blocks were all emergent from the water column. Water flowing over the top of the block decreased the gradients formed by flow around the block edges. The maximum change in velocity in the y direction (du/dy) for Site 14 was 1.3 $(cm.s^{-1}).cm^{-1}$ (Figure 1) compared to 4.8 $(cm.s^{-1}).cm^{-1}$ at site 21 (Figure 4) where the block is not submerged. This difference in velocity gradients may have affected the dissipation of kinetic energy and impaired the creation of eddies at the block corners.

Fish Use of Habitats

Habitats with blocks achieved the goal of creating low velocity areas (Table 3), yet fishes were rare in these sites compared to natural sites (Figure 11). During snorkel surveys some fishes were observed approaching the blocks but veered around them as they moved upstream. In other locations, fish approached the area behind the block when fleeing from a snorkeler, but they did not remain in the vicinity of the block after the snorkeler had left the area. Finally, two blocks placed in riffles experienced sand deposition in the downstream area of low velocity, creating depths of less than 10 cm. Because riffles are already shallow, this factor may have made fishes less likely to consider the location suitable for resting, particularly if they were larger than young of the year and more exposed to predation.

Of the ten modified sites in this experiment, four showed increases in mean fish abundance classes after the structures were added, three of the ten experienced a decrease in fish abundance and three sites never had a single fish sighting (Table 4). These results were unexpected, and could have several reasons. The failure of the modifications in general to attract fishes to the low velocity sites may be related to differences in the velocity patterns created in the modified sites compared to those found in natural habitats occupied by fishes. The range of velocities created downstream of the blocks did not correspond with the velocity ranges in natural flow shelters, such as pools. The velocity gradients created by the edges of the blocks may have proven difficult for fishes to navigate. The changes in velocity direction created downstream of the blocks may have been incompatible with rheotaxis, or the response of fishes to face into an oncoming current (Vogel 1994). Turbulence intensity values were also higher in modified habitats than in natural ones, which have negative implications for the ability of fishes to maintain stability (Liao 2007).

Discussion

In-stream structures designed to improve or create fish habitat generally fit into two categories: those which modify flow patterns and those which stabilize banks (Roni et al. 2005). The structures in this experiment belong to the first category. The goal of this work was to create flows which resembled those in a pool habitat by placing structures in the runs and riffles of a warm water stream. Refuge habitat is valuable for many fish behaviors and is thought to be limiting in warm streams (Lobb and Orth 1991). Therefore, it was expected that structures placed in the flow would create low velocity areas downstream that fish would use. The metric for success was not increased abundance over the length of the stream, but rather the presence of fish in an area of stream where previously no individuals or shoals had been seen.

The differences in seven measured site characteristics listed in Table 6 were tested for significance using SPSS. Of the seven characteristics measured, only site depth has a significant ($p<0.05$) Pearson correlation with fish abundance. Current speed (U), as measured with the Marsh-McBirney after blocks were installed, has a strong correlation with the number of blocks. This supports the observation that the installation of the blocks did reduce local velocities, but this was not followed by an increased abundance of fishes at the modified sites. Fish abundance also did not show a significant trend toward other site characteristics, including substrate type. Due to the small number of sites where a complete set of ADV measurements were taken (one pool habitat, one one-block site and two three-block sites) it was impossible to conduct tests of statistical significance on calculations done with ADV data, including TI, TKE, and variance.

Average velocity is a common measure of fish habitat and is a design variable in construction of fishways and fish ladders around dams (Enders et al. 2009b, Odeh 2003). It is known that fish often seek habitats with a range of velocities available in a small area. Salmonids have been shown to prefer focal points which have a lower velocity than those of their surroundings. The location of higher velocities nearby then facilitates drift feeding (Enders et. al 2009a, Smith et al. 2005). The environments created by the blocks in this study were meant to mimic this preference. In this experiment, the range of velocities measured in the pools overlapped with the velocity ranges created by the blocks (Figure 10), hence it was predicted that fishes would use these new locations. However, the low velocity values created by the blocks were consistently quite close to zero or negative, and were reduced from unmodified current speeds of 12 to 60 $cm.s^{-1}$ in runs and riffles (Figures 4, 6, and 8). Velocity values measured in the comparison pool, however, were near zero only in the shallowest water at the edges. Fishes were consistently seen in the center of the pool where velocities ranged from 12 to 18 $cm.s^{-1}$ (Figure 9). Thus average velocities created by the modifications appear to have been too low compared to those within pools that fishes preferred.

Despite its common use as a metric for suitable fish habitat, some current literature suggests that fish are more sensitive to measurements of turbulence, such as TI (Cotel et al. 2006) than velocity. In this experiment, the low velocities created downstream of the blocks had larger variations over time than the pool sites where more fishes were observed (Table 5). This led to higher TKE and TI values than those measured in pools. The ability of fishes to stabilize their posture and swimming patterns are affected by the average momentum and energy of their surroundings relative to variations of these qualities (Lupandin 2005, Enders et al. 2003). Increased TKE and TI values signify that the flow patterns behind the blocks would tend to challenge fish stability by creating very large and variable perturbations with little or no damping of disturbances by the surroundings. With little flow over the body and fins at these average velocities, a fish would have to respond to small temporal changes in momentum and energy with active propulsion (Altringham and Ellerby 1999). This would make swimming and maintaining stability in this habitat more energetically costly than in a faster current (Lupandin 2005), where flow around the body would contribute to stability.

These control problems are likely to have been exacerbated by the changing velocity orientation behind the blocks. In the comparison pools, velocities were always positive with respect to the environmental coordinate system described earlier. However, velocities measured directly behind the blocks were opposite of the main channel current direction. Because of this, a fish attempting to hold a steady position in the flow would have had to frequently change orientation with respect to a fixed point in the habitat, such as the block itself. Maintaining positive rheotaxis involves sensory inputs from the acoustic-lateralis and optic systems (Caillet et al. 1996, Engelmann et al. 2000). A fish will feel the flow of water past its body as well as see its motion relative to the environment. In this experiment, these two systems would provide the same information to a fish's brain if that fish was in a pool, but would contradict each other if the fish was behind a block. The fish behind the block would feel surrounded by flow in one direction but see objects in the flow a short distance away moving in the opposite direction. This situation would make the maintenance of positive rheotaxis extremely difficult and probably discourage fish from using the blocks as resting or feeding habitat.

Although fish generally select stream habitats where there are spatial velocity gradients present (Liao 2007), they tend to select intermediate values from the range available to them. In areas where the velocity remains relatively constant in space, focal points, which facilitate low speed swimming, will be distant from higher velocities regions with increased delivery of food items. Where velocity changes rapidly in space, fishes demonstrate behavior patterns which indicate avoidance of accelerating flows which might endanger stability. Enders et al. (2009a) studied the threshold at which salmonids would avoid a velocity gradient, and found that fish would avoid lower velocities which they were subject to with negative rheotaxis. Fish which approached a high velocity gradient with positive rheotaxis could handle higher accelerations and were more likely to swim quickly away from accelerating flows rather than turn to avoid them. The velocity contours show clearly the velocity gradients created by the blocks were especially sharp on configurations in riffles (Figures 4 and 6). If fish do avoid rapid accelerations in space, these velocity gradients may have acted as a barrier towards using the blocks as refuges. This is consistent with field observations from this experiment in which fishes swerved around the blocks rather than use them as flow refuges as they moved upstream. Ways to reduce these gradients include orienting blocks at an oblique rather than perpendicular angle to the flow or making them porous so that the current can move through as well as around the structure.

Velocity gradients are generated by many naturally occurring structures in streams, such as large woody debris, substrate material, and vegetation. Fish need and have been shown to use in-stream structures on a variety of scales from fine-scale structures of less than 20% Total Length (TL) to large woody debris greater than 4x TL in field settings (Webb 2006, Bachman

1984). The blocks used in this experiment were on the same scale as large woody debris with a streamwise dimension of 20 cm. However, blocks differed from large woody debris because the former had sharp corners as compared to the rounded edges of most natural obstructions. These sharp edges create stronger velocity gradients and greater TI and TKE that appear to deter fish (Shamloo et al 2001).

Additionally, fishes may have not sampled the stream reach with enough frequency to find the newly created habitats. Lotic species sample stream habitats on a variety of temporal scales, from diel to seasonal to yearly (Brewer and Rabeni, 2008). However, the cyprinids which were most common in this stream did not appear to move through riffles and runs very frequently, meaning that they simply may not have discovered the modified sites. Even if the flow environments created by the blocks had been suitable for fish use, they were located in the thalweg of the stream without cover and surrounded by flow patterns which fishes may have found difficult to navigate. Also, the time frame of the experiment was less than three months, and it may have taken a season or more for fishes to discover and colonize any new habitats.

Finally, there is some evidence that velocity and turbulence characteristics of streams cause migratory behavior in some fishes (Tiffan et al. 2009). If this is the case, velocity and turbulence values which are too high or too low could actually prevent fish from completing seasonal movements and further impede habitat sampling. This issue is of greatest importance for larger structures and more extensive modifications than those involved in this study.

This experiment suggests four factors should be considered in order to improve the effectiveness of in-stream flow structures for increasing fish abundance. First, smaller bluff bodies which are completely submerged in the flow would provide more natural velocity gradients and minimize edge effects (Shamloo et al. 2001). Second, round structures without corners would decrease eddy formation (Ozgoren 2005). This concept has been used in the installation of logs or half-logs (Wills et al. 2004), groins and boulders (Stewart et al. 2009) and check dams (Binns 2004). Third, structures with gaps or holes which allow flow to pass through them would decrease the formation of large spatial velocity gradients and help create a turbulence regime more similar to that found in unmodified flow areas and natural pools. This concept has been used in products such as Aqua Cribs (Great Lakes Products, Inc., Wisconsin, U.S.A). Wills et al. (2004) installed Aqua Cribs in the Au Sable River in central Michigan but found that smallmouth bass (*Micropterus dolomieu* Lacepéde) preferred half-log structures to the Aqua Cribs. Finally, structures must be evaluated on an appropriate time scale based on local fish movements and migration patterns.

Figures and Tables

Table 1- Distribution of current speeds, depth, and substrate for 15 locations spanning the range of current speed, depth and substrate along the stream reach studied for the East Maple River.

Five sites were assigned to be unmodified controls, ten were modified with a single block, and of these five were further modified with the addition of a two additional blocks. Mean current speed was measured with a Marsh-McBirney electromagnetic flowmeter. Presence of large woody debris and substrate composition were estimated visually to the nearest 5% using a transparent-bottomed bucket.

Site Number	**Site Type**	**5 sec mean speed ($cm.s^{-1}$)**	**Depth (cm)**	**Site Location**	**% sand**	**% gravel**	**% LWD**
2	1 block	65	16	Riffle	25	75	0
3	3 blocks	45	25	Run	45	55	0
5	Reference	42	26	Run	85	15	0
7	1 block	17	26	Run	25	75	0
8	Reference	16	20	Run	100	0	0
12	3 blocks	47	16	Riffle	30	70	0
14	3 blocks	36	34	Run	5	95	0
16	1 block	25	27	Run	95	5	50
19	Reference	30	27	Run	5	95	0
21	3 blocks	65	15	Riffle	0	100	0
24	Reference	55	16	Riffle	85	15	0
25	3 blocks	69	28	Riffle	25	75	10
30	1 block	10	16	Run	95	5	40
34	1 block	25	16	Riffle	35	0	0
35	Reference	37	22	Run	35	65	0

Table 2- Abundance Classes

Relative abundance of fishes at each site was estimated in terms of abundance classes based on the estimated number of individuals. Actual numbers could not be determined with accuracy because of fish movements.

Abundance Class	Number of individuals counted
0	0
1	1
2	2 to 5
3	6 to 10
4	11 to 20
5	>20

Table 3- Measured flow speeds before and after modification.
Flow speeds were measured with a Marsh-McBirney and averaged over 5 seconds. Speeds at unmodified and reference sites were measured at the site marker. Speeds at modified sites were measured at 5 cm downstream of block configuration centerline.

Site #	**Site Location**	**Site Type**	**Flow speed ($cm.s^{-1}$) before modification**	**Flow speed ($cm.s^{-1}$) after modification**
2	riffle	1 block	55.0	-2.0
3	run	3 blocks	45.0	-2.0
5	run	Reference	42.0	23.0
7	run	1 block	17.0	0.0
8	run	Reference	16.0	7.0
12	riffle	3 blocks	47.0	-4.0
14	run	3 blocks	36.0	-1.0
16	run	1 block	25.0	-3.0
19	run	Reference	30.0	11.0
21	riffle	3 blocks	65.0	-2.0
24	riffle	Reference	65.0	46.0
25	riffle	3 blocks	69.0	-3.0
30	run	1 block	10.0	-2.0
34	riffle	1 block	25.0	2.0
35	run	Reference	37.0	23.0

Table 4- Fish Abundance Classes for 15 Study Sites

Fish distribution was recorded using snorkel surveys. Each site was visited twice before being modified. After adding one block to ten sites, all fifteen sites were surveyed twice, and after the addition of three blocks to five of the ten single block sites, all fifteen were surveyed twice more. Fishes were counted if they were within one square meter downstream of the center of the block configuration in modified sites or within one square meter of the site marker in unmodified sites.

Site # and type	Initial Survey	Zero Blocks		First Modification	Zero Blocks		Second Modification	Zero Blocks	
2 (riffle)		0	0		0	0		0	0
5 (run)		3	3		0	2		0	0
8 (run)		5	2		5	3		4	4
19 (run)		3	2		5	5		5	4
35 (run)		3	3		2	0		0	0
Site # and type		Zero Blocks			One block			One block	
7 (run)		2	3		5	0		2	0
16 (run)		0	0		0	0		0	0
24 (riffle)		0	0		0	0		0	0
30 (run)		0	2		5	4		0	0
34 (riffle)		0	0		0	2		2	2
Site # and type		Zero Blocks			One block			Three Blocks	
3 (run)		0	0		0	0		1	0
12 (riffle)		0	0		0	0		0	0
14 (run)		5	2		4	0		1	2
21 (riffle)		3	0		0	0		0	0
25 (riffle)		1	0		1	0		0	3

Table 5- Comparison of statistical and physical flow characteristics between comparison pool and a single riffle site before and after modification.
Edge measurements are at the outside of block configurations and the shallowest pool location where it was possible to take ADV data. Center measurements are at the middle of block configurations and the deepest point of the pool.

	Comparison Pool		Unmodified Site 34 (riffle)		Modified Site 34 (riffle)	
Location	Edge	Center	Edge	Center	Edge	Center
Mean U_R ($cm.s^{-1}$)	10.08	10.41	13.33	14.97	10.79	3.08
TI	0.28	0.33	0.19	0.24	0.62	0.40
TKE ($cm^2.s^{-2}$)	25.26	24.04	15.13	145.00	79.58	5.48
σ of Mean U_R ($cm.s^{-1}$)	2.85	3.46	2.57	3.58	6.66	1.23
Variance of Mean U_R ($cm^2.s^{-2}$)	8.14	12.00	6.61	12.79	44.38	1.52

Table 6- Statistical Correlations Between Site Descriptions

Bivariate analysis was done using SPSS on seven site characteristics. Current speed measurements are from Marsh-McBirney data and abundance values from snorkel surveys. Bold text indicates p<0.01, italic text indicates p<0.05.

		Blocks	Depth	U	Abundance	Sand	Gravel	Pebble
Blocks	Pearson Correlation	1.000	0.075	**-0.591**	-0.185	**-0.309**	**0.318**	-0.046
	Sig. (2 tailed)		0.508	0.000	0.100	0.005	0.004	0.688
	N	80	80	80	80	80	80	80
Depth	Pearson Correlation	0.075	1.000	-0.181	*0.270*	-0.204	**0.304**	*-0.268*
	Sig. (2 tailed)	0.508		0.109	0.016	0.070	0.006	0.016
	N	80	80	80	80	80	80	80
U	Pearson Correlation	**-0.591**	-0.181	1.000	-0.157	0.024	0.003	-0.064
	Sig. (2 tailed)	0.000	0.109		0.164	0.835	0.982	0.570
	N	80	80	80	80	80	80	80
Abundance	Pearson Correlation	-0.185	*0.270*	-0.157	1.000	0.019	0.027	-0.114
	Sig. (2 tailed)	0.100	0.016	0.164		0.867	0.815	0.315
	N	80	80	80	80	80	80	80
Sand	Pearson Correlation	**-0.309**	-0.204	0.024	0.019	1.000	**-0.920**	-0.125
	Sig. (2 tailed)	0.005	0.070	0.835	0.867		0.000	0.271
	N	80	80	80	80	80	80	80
Gravel	Pearson Correlation	**0.318**	**0.304**	0.003	0.027	**-0.920**	1.000	*-0.274*
	Sig. (2 tailed)	0.004	0.006	0.982	0.815	0.000		0.014
	N	80	80	80	80	80	80	80
Pebble	Pearson Correlation	-0.046	*-0.268*	-0.064	-0.114	-0.125	*-0.274*	1.000
	Sig. (2 tailed)		0.016	0.570	0.315	0.271	0.014	
	N	80	80	80	80	80	80	80

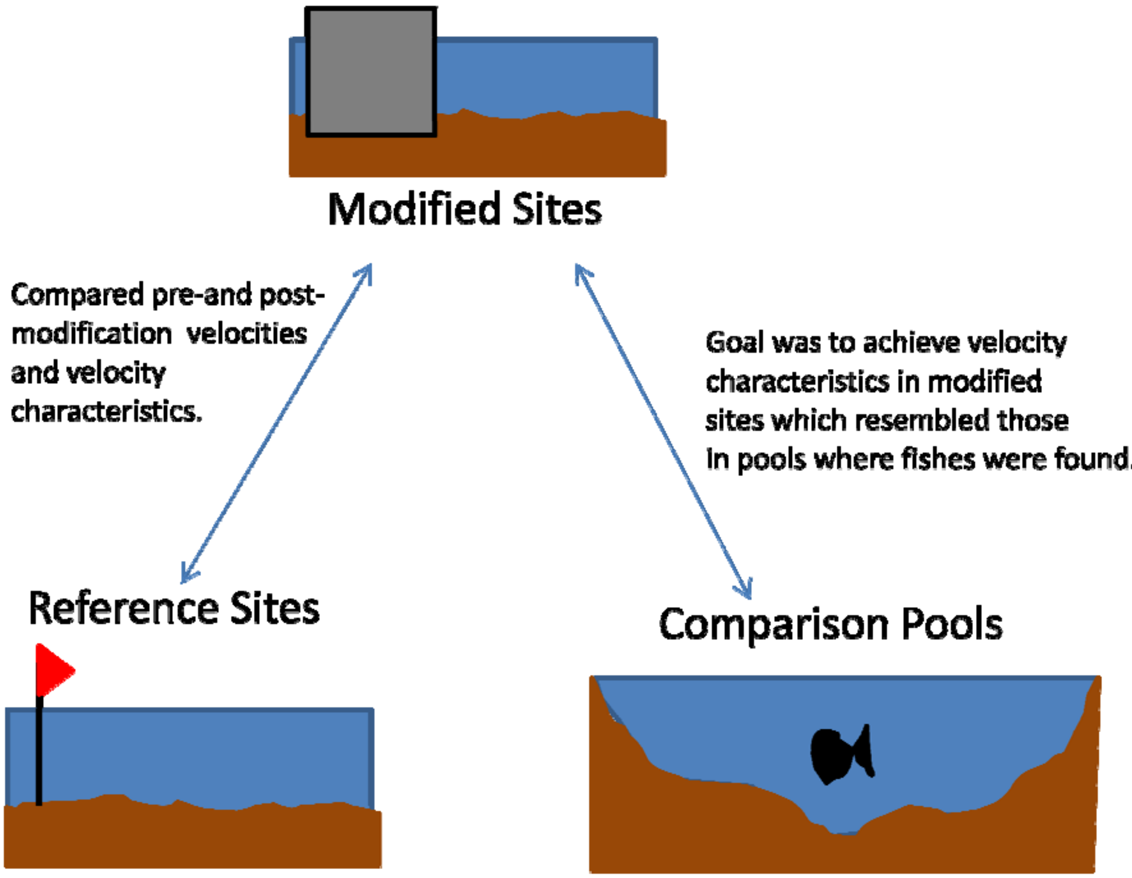

Figure 1- Profile view of the three site types studied in this experiment.

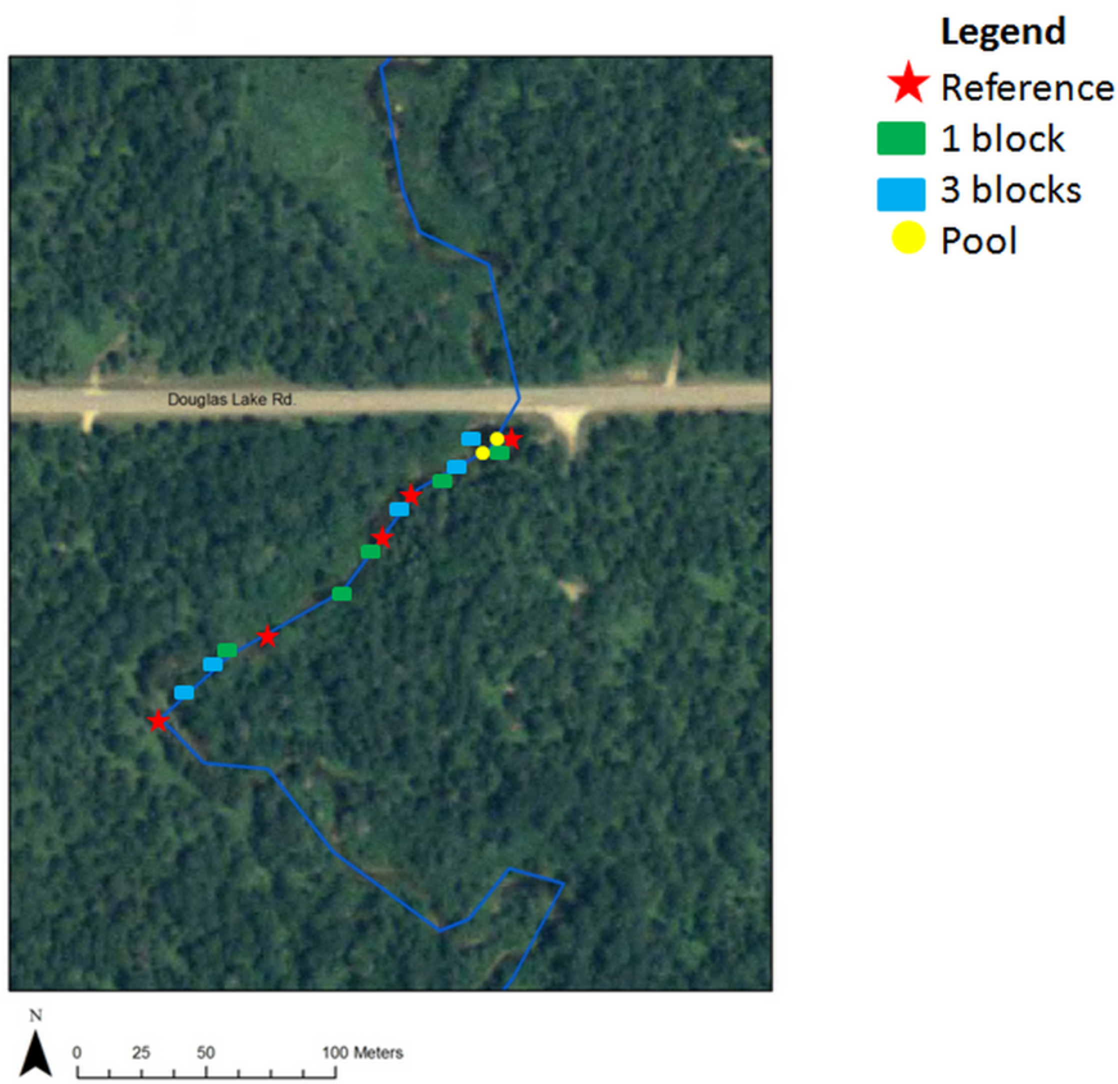

Figure 2- Research Site on the Maple River, East Branch

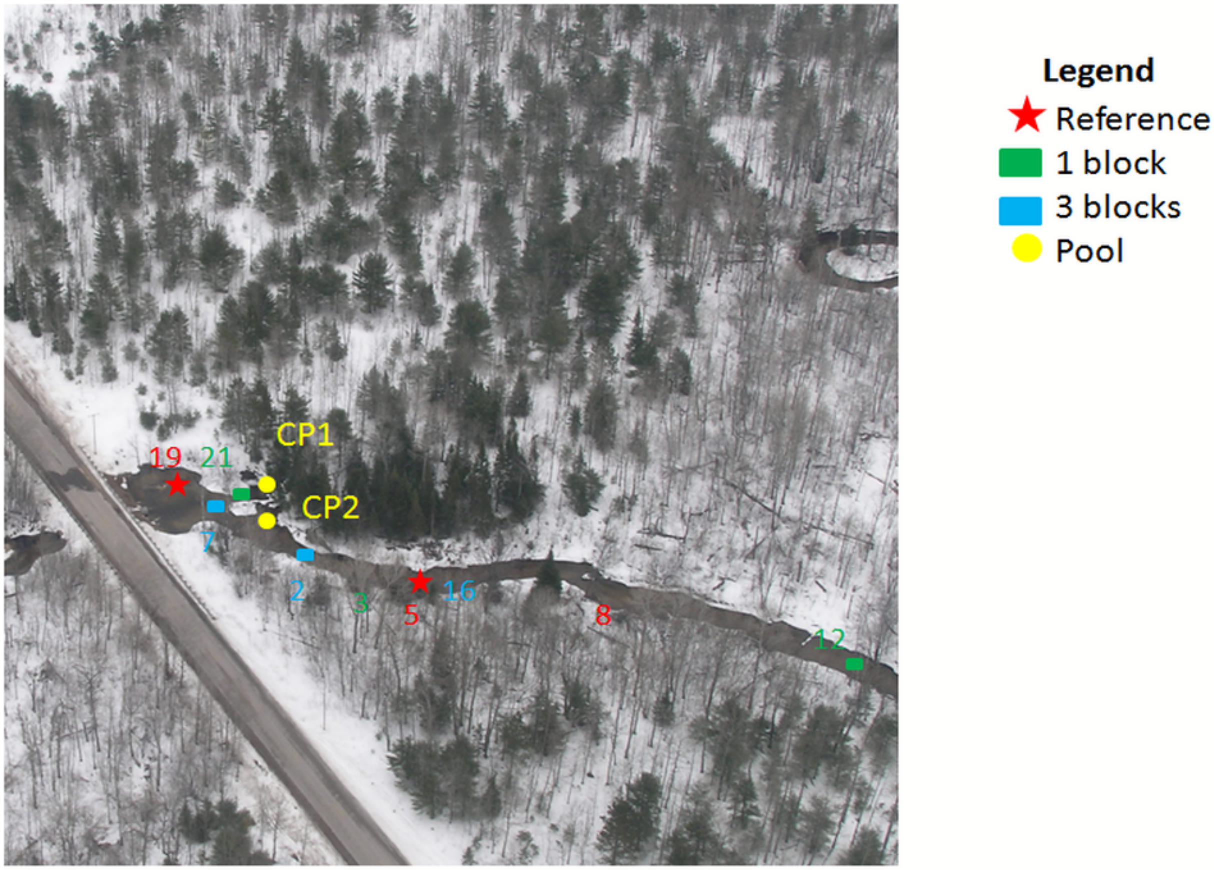

Figure 3-
Close-up of 11 sites at upstream end of stream reach.

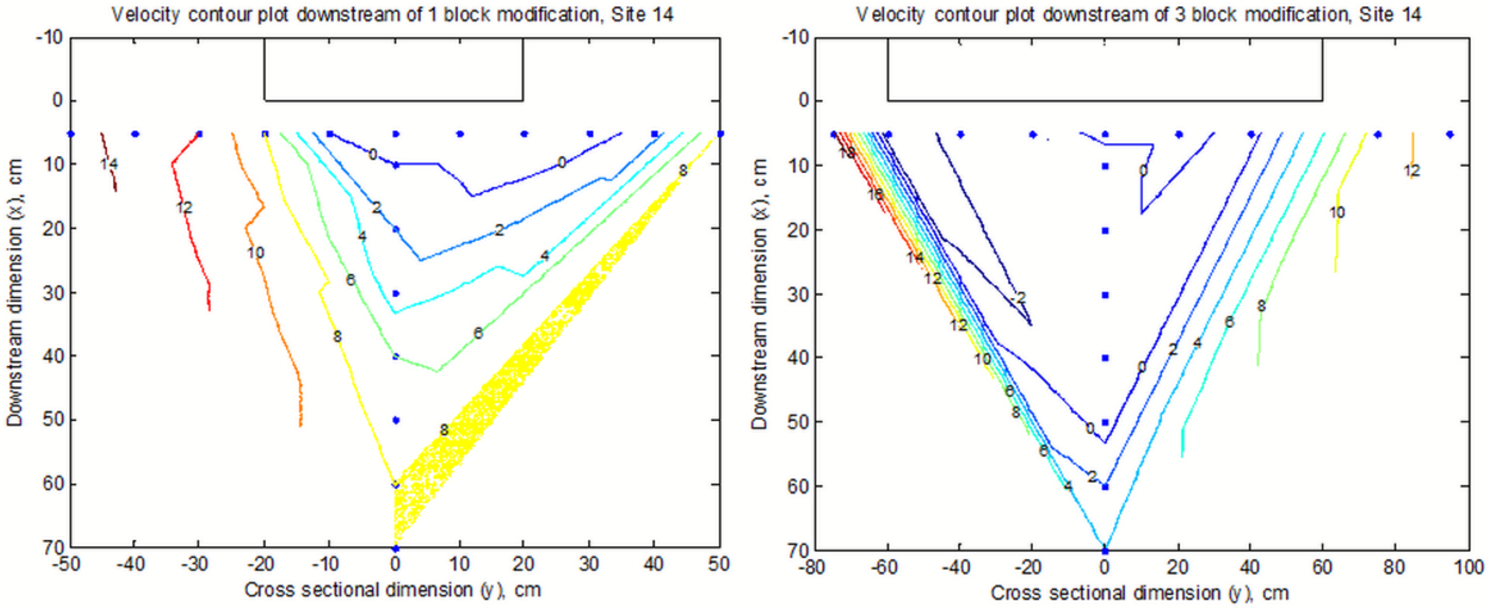

Figure 4- General flow patterns were measured downstream of each modification type following the insertion of one block (left) and three blocks (right). Starting from a reference point 5 cm downstream from the center of the block (x=0 cm, y=5 cm) mean current speed was measured using a Marsh-McBirney electronic flow meter at 10 cm intervals up to 50 cm across the flow on each side (cross stream distance along the x axis) and at 10 cm intervals up to 70 centimeters downstream of the center of the block (downstream distance along the y axis). Locations where current speed was measured are shown as squares. In-stream flow direction is from top to bottom of figures.

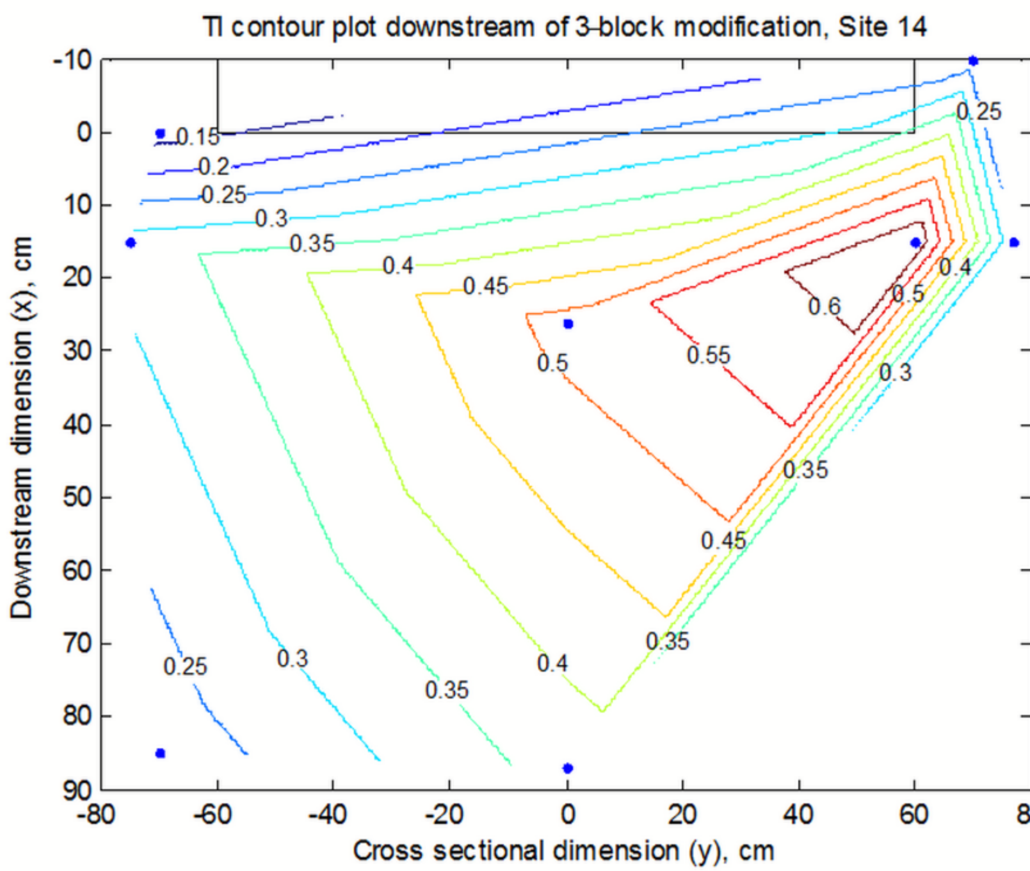

Figure 5- Turbulence Intensity values were calculated downstream of the three-block configuration. Data was collected using a Nortek Acoustic Doppler Velocimeter (ADV) set at 25 Hz for 120 seconds at a constant depth of 4 cm from the substrate. Measurements were taken at points of visible surface eddy formation around block corners as well as in the intended shelter area downstream of the blocks. Locations of ADV measurements are shown as squares. In-stream flow direction is from top to bottom of figures.

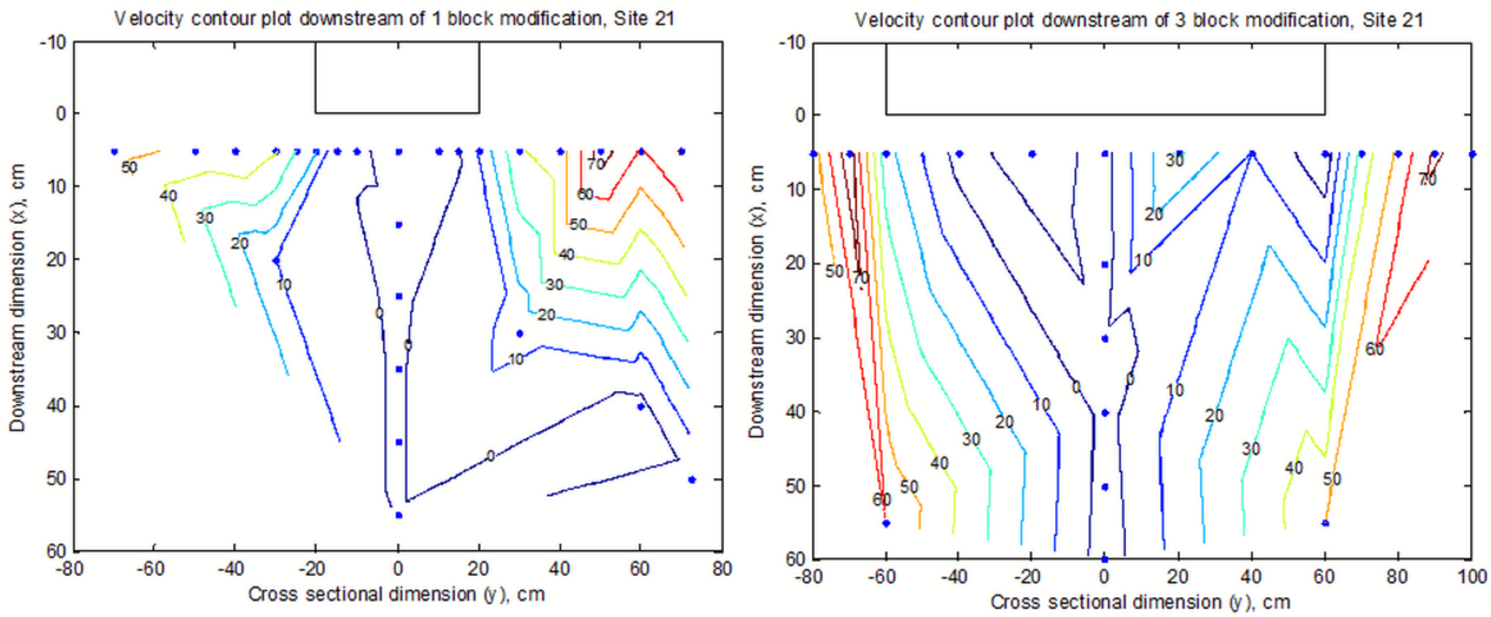

Figure 6- General flow patterns were measured downstream of each modification type following the insertion of one block (left) and three blocks (right). Starting from a reference point 5 cm downstream from the center of the block (x=0 cm, y=5 cm) mean current speed was measured using a Marsh-McBirney electronic flow meter at 10 cm intervals up to 50 centimeters across the flow on each side (cross stream distance along the x axis) and at 10 cm intervals up to 70 cm downstream of the center of the block (downstream distance along the y axis). Locations where current speed was measured are shown as squares. In-stream flow direction is from top to bottom of figures.

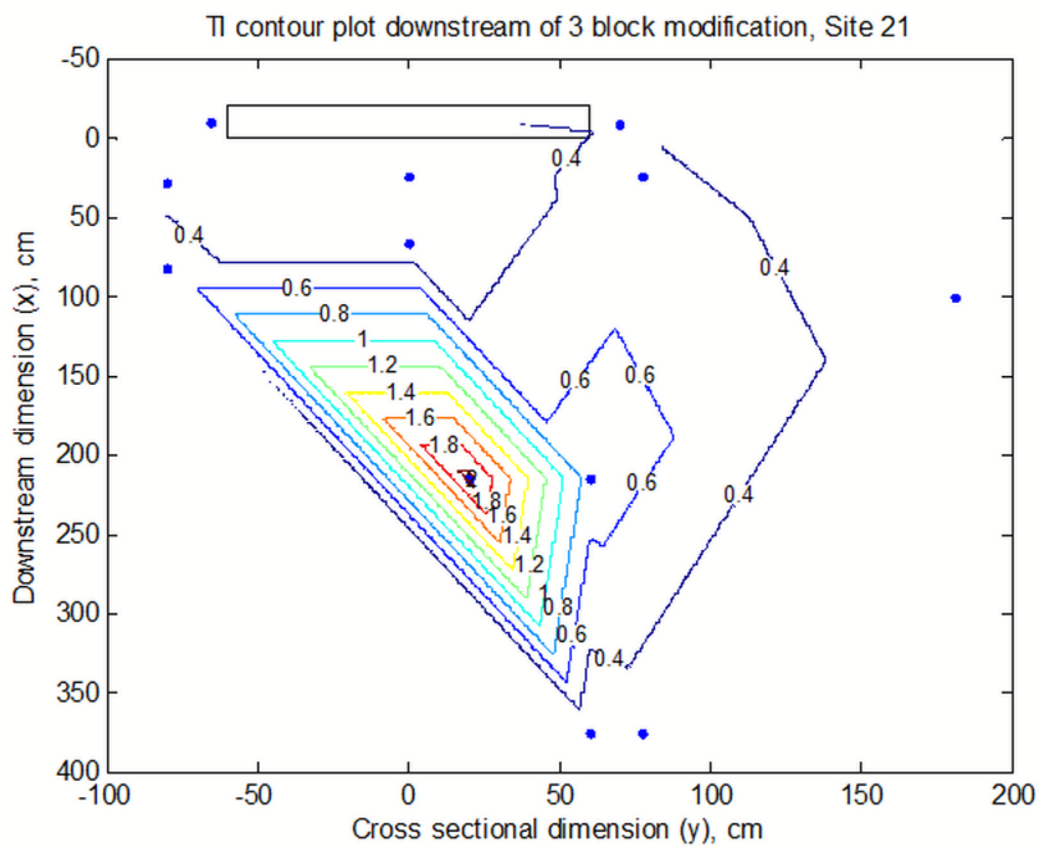

Figure 7- Turbulence Intensity values were calculated downstream of the three-block configuration. Data was collected using a Nortek Acoustic Doppler Velocimeter (ADV) set at 25 Hz for 120 seconds at a constant depth of 4 cm from the substrate. Measurements were taken at points of visible surface eddy formation around block corners as well as in the intended shelter area downstream of the blocks. Locations of ADV measurements are shown as squares. In-stream flow direction is from top to bottom.

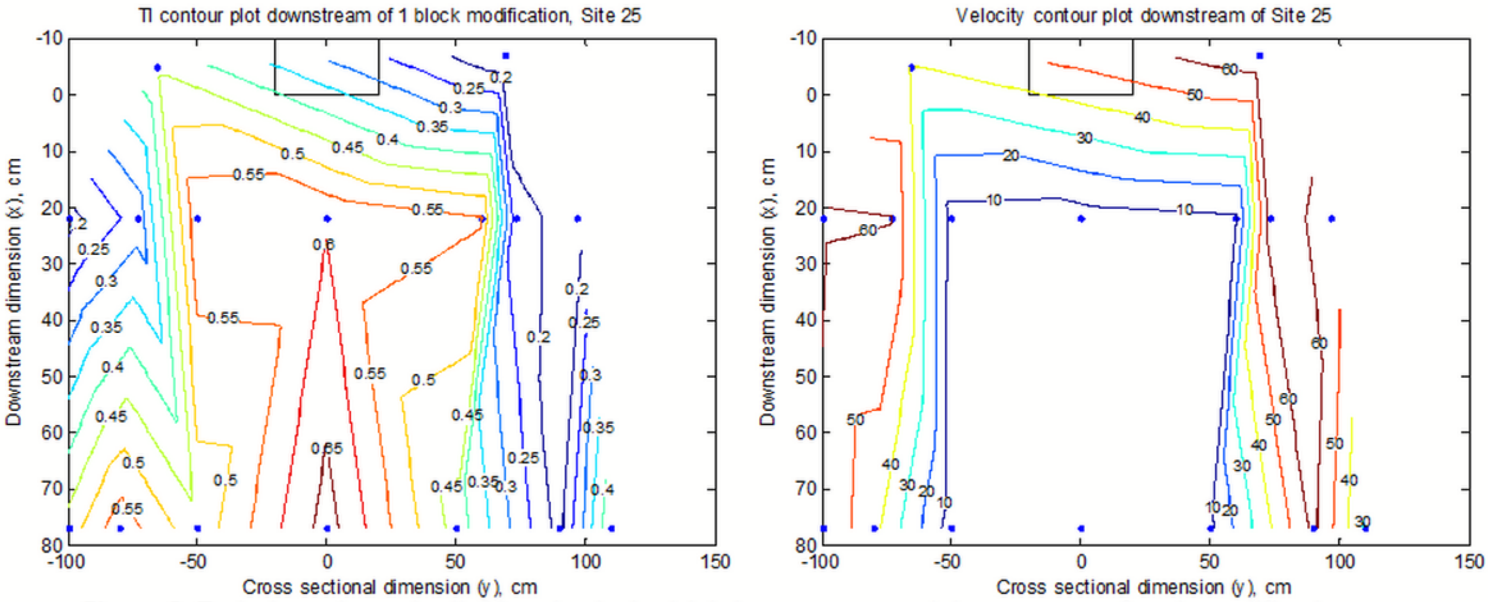

Figure 8- Turbulence intensity (left) and velocity (right) were measured downstream of each modification type following the insertion of one block (left) and three blocks (right). Starting from a reference point 20 cm downstream from the center of the block (x=0 cm, y=20 cm) mean current speed was measured using a Marsh-McBirney electronic flow meter. ADV measurements were taken in the same locations as Marsh-McBirney measurements. Measurement locations are shown as squares. In-stream flow direction is from top to bottom of figures.

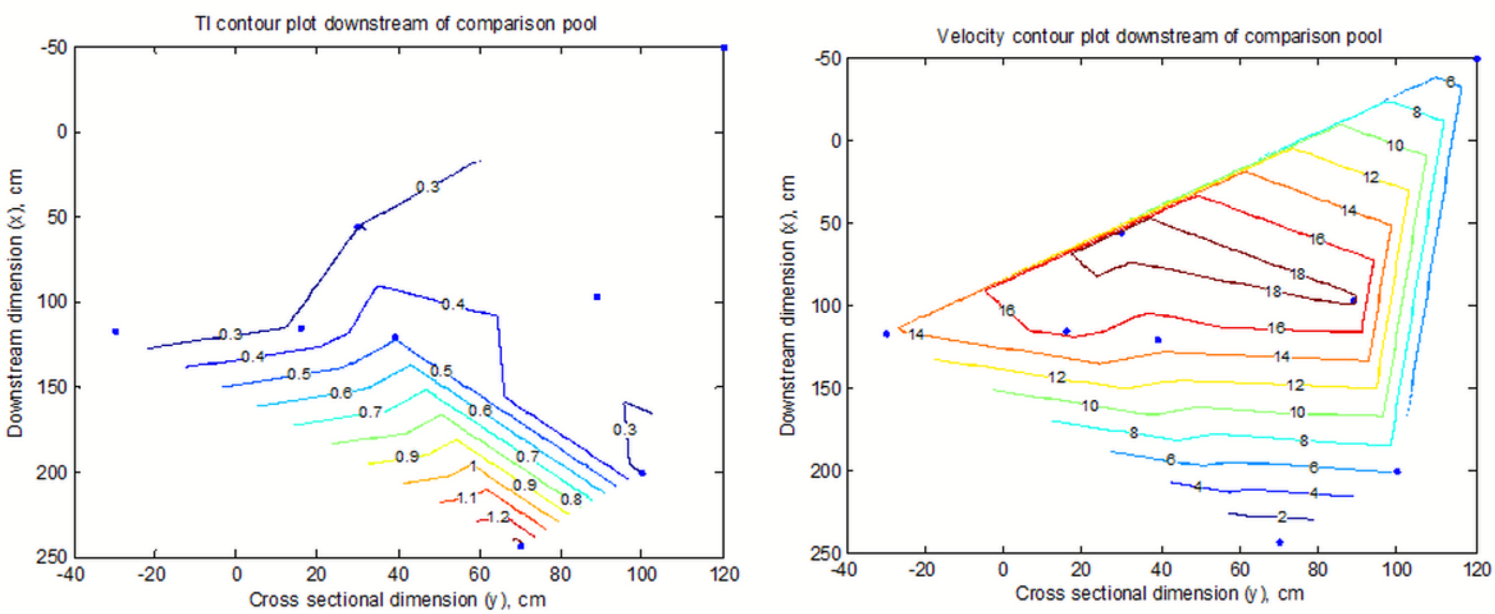

Figure 9- Turbulence intensity (left) and velocity (right) were measured in a comparison pool using an ADV and Marsh-McBirney, respectively. Measurements were taken in the center, at the inlet and outlet, and at the pool edges. ADV measurements were taken in the same locations as Marsh-McBirney measurements. Measurement locations are shown as squares. In-stream flow direction is from top to bottom of figures.

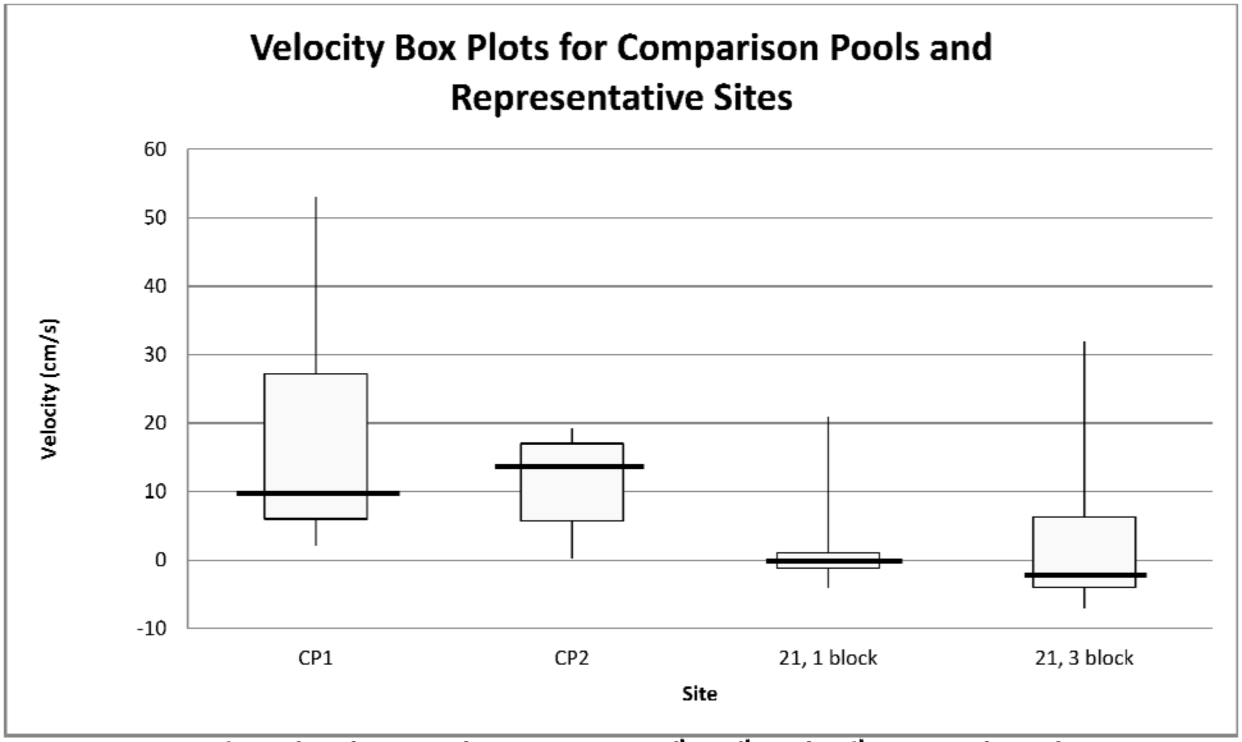

Figure 10- A box plot showing the minimum, 25th, 50th and 75th percentile and maximum velocity values measured at one modified site with two different types of modification and two unmodified comparison pools. Percentiles are calculated from the total number of velocity measurements taken at each site, which ranged from 26 in CP 1 to 8 in CP 2.

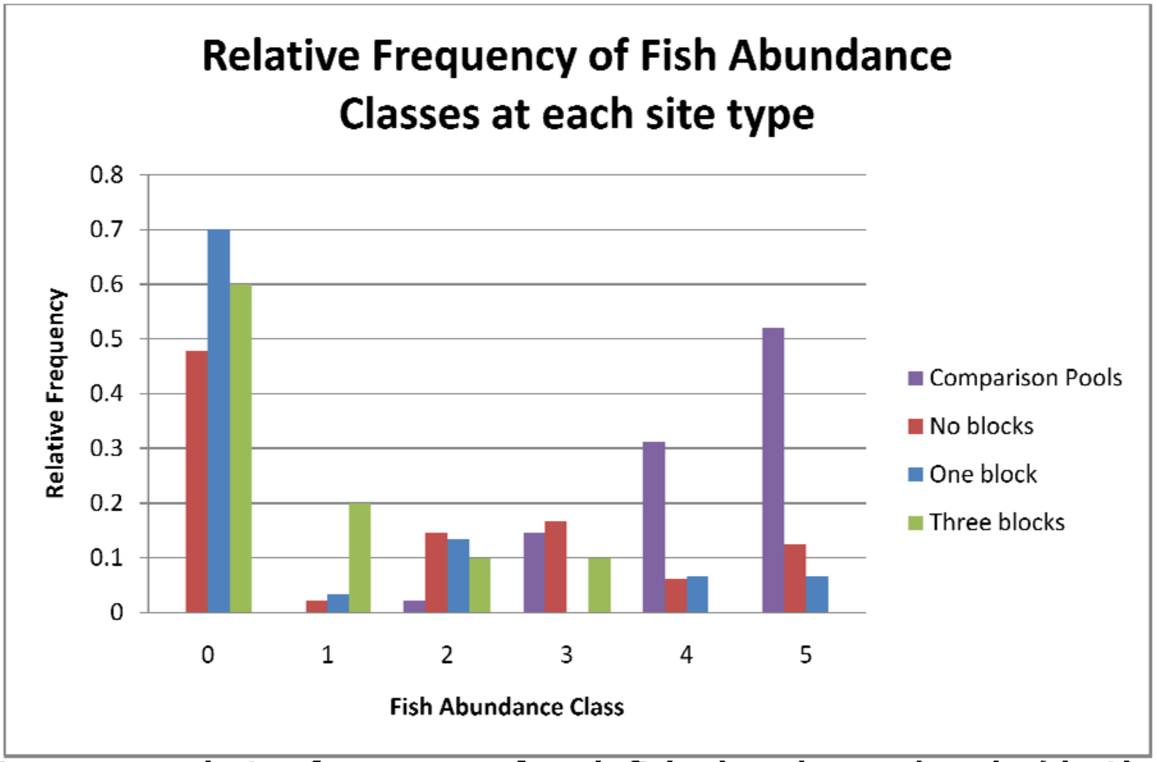

Figure 11- Relative frequency of each fish abundance class (Table 2) observed at each site type. Number of observations n = 48 for comparison pools and no-block sites, 30 for one-block sites and 10 for three-block sites. Comparison pools consistently show larger abundance classes than modified sites and abundance classes above 3 are never observed at three-block sites.

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