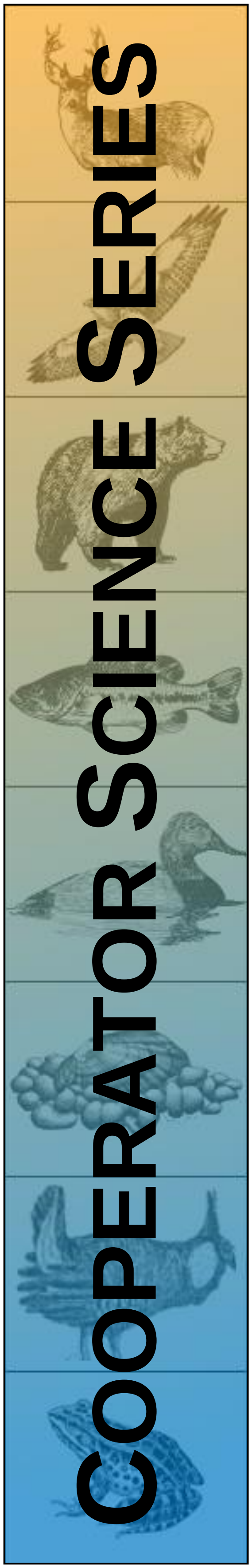

Establishing links between stream flow and ecological integrity in the Sudbury River (Northeastern U.S.)

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Cooperator Science Series # 122-2016

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Final Report

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Abstract

With increased pressure from a growing human population, managers are challenged to understand how novel disturbances (e.g., climate change, increased water withdrawals, urbanization) may affect natural resources. The Sudbury River is a National Wild and Scenic River located in suburban Boston, Massachusetts (Northeastern US) with myriad impairments (e.g., mainstem impoundments, withdrawals, and urbanization) that is under increasing pressure from hydrologic alteration. We sampled fish, mussel, and macroinvertebrate assemblages in the Sudbury River and used species traits to investigate potential effects of past and future flow alteration on biota. Analysis of 33 years of stream gage data indicates continued hydrologic alteration of the Sudbury River, likely related to increased urbanization and water withdrawals over that time. These changes include a roughly 200% increase in rise rates of flows, an approximate 65% decrease in 1-day minimum flows, and a trend towards increasing high flow pulse counts. Biotic sampling in summer of 2014 demonstrated that the Sudbury River is now dominated by generalist species. Of five mussel species sampled, all are generalists in their habitat requirements. Though one mussel species of special concern was sampled, the most abundant species collected were the widespread Eastern elliptio (58%) and Eastern lampmussel (40%). We used the target fish community (TFC) model to assess the degree to which the fish assemblage deviated from that expected for a river with similar zoogeographic and physical features. Overall, the current community has a 22.7% similarity to the TFC. Of the four fluvial specialist species present in the TFC, only fallfish was sampled in our study. While the TFC showed that the historical assemblage was likely dominated by fluvial specialist and fluvial dependent species, the current assemblage is overwhelmingly dominated by macrohabitat generalists (90.6% of fishes sampled). These results are consistent with other studies that show shifts in assemblages from fluvial specialists to habitat generalists with hydrologic alteration. If the current trends continue, it is likely that biotic assemblages will experience increasing pressure from hydrologic alteration. While hydrologic alteration is likely impacting biotic assemblages in the Sudbury River, other factors such as high temperatures, low dissolved oxygen, high nutrients, low availability of high-quality habitat, and poor habitat connectivity may also be negatively impacting biotic assemblages. Comparisons to other rivers and a complete longitudinal habitat survey could help to identify availability of unique habitats and representativeness of this study. While this study suggests impacts of flow on biota, future studies with quantitative, habitat-specific sampling during different flow levels could help to directly identify links between hydrologic alteration and biotic impairment in the Sudbury River.

Introduction

Rivers and streams are defined by flowing water, making them unique among aquatic systems. Such lotic systems have a natural flow regime that is determined by regional weather patterns, stream gradient, and geomorphology (Poff and Zimmerman 2010). A stream generally has a characteristic cycle of high flows and low flows, as well as extreme events such as floods and very low flows. Within this pattern, there is a natural range of variability in terms of timing and magnitude of flows (Richter et al. 1996, Poff et al. 1997, Richter et al. 1997). Typically, high flows are dominated by surface water runoff from storm events or snow melt while low flows are dominated by groundwater inputs (Gore 2006).

It is well recognized that the natural flow regime is one of the primary drivers of the ecology of lotic systems (Poff et al. 1997, Richter et al. 2003). Riverine biota are adapted to the seasonal patterns of flow that are typical for a specific system (Moyle and Light 1996, Bunn and Arthington 2002, Lytle and Poff 2004). Timing of low or high flows can be important cues for life cycle transitions, such as spawning and migration (Montgomery et al. 1983). Some species depend on fast velocities for spawning habitat and other life history events (Jones et al. 1999), and some demonstrate local morphological adaptations to the flow regime of a particular river (Taylor 1991). Episodic flood events that inundate the floodplain can be important for riparian vegetation and inputs of large wood, and can have important effects on population dynamics of aquatic organisms (Stanford 2006, Poff and Zimmerman 2010). Additionally, flow directly impacts habitat by shaping channel morphology, bed texture, and sediment transport (Bunn and Arthington 2002). Disruptions to the natural flow regime, such as prolonged low flows, changes in timing of flow events, or changes to variability in flows, can adversely impact native species and favor the establishment of introduced species and habitat generalists (Poff and Allan 1995, Moyle and Light 1996, Freeman and Marcinek 2006, Olden et al. 2006).

The recognition of the interdependence between the natural flow regime and biotic communities has led to a shift in the management of lotic systems. In the past, managers tended to focus on targeting minimum flows or other simple metrics. Such approaches neglect aspects of the flow regime that are critical to ecological integrity (Stalnaker 1990). In recent years, some scientists have recommended moving towards maintaining a system within a certain percentage of its historic range of variability (Poff et al. 1997, Richter et al. 1997, Poff et al. 2010). The goal of this approach is to better maintain the hydrological conditions which led to the development of a stream's historic biotic community, thereby favoring native species (Baron et al. 2002). Other scientists have directly quantified the relationship between components of the flow regime and fish assemblages (Roy et al. 2005, Knight et al. 2008, 2014). Both approaches highlight the importance of incorporating multiple aspects of the flow regime (not just minimum flows) to protect or restore natural ecosystem structure and function.

These approaches to managing water resources for ecological integrity often come in direct conflict with management for human uses, such as water supply (for drinking, irrigation, and industry) and flood control. Human demands are expected to increase in the future, likely increasing conflicts between the demand for human extraction and the desire to maintain ecological integrity (Postel et al. 1996). Sustainable use of water resources requires balancing human and ecosystem needs (Baron et al. 2002, Richter et al. 2003). These challenge of balancing uses is particularly acute in urban systems, where demand on water resources are most intense.

Urbanization results in numerous impacts on aquatic ecosystems beyond water abstraction. Increases in impervious surfaces directly alter the hydrology of lotic systems, resulting in increased magnitude and volume of storm flows, flashier flows with rainfall, and altered base flows (Konrad and Booth 2005, Roy et al. 2005, Shuster et al. 2005). This change in hydrology, combined with increased contaminants and nutrients from point and non-point sources in urban areas, results in altered thermal regimes, water quality, and geomorphology in urban streams (Paul and Meyer 2001, Walsh et al. 2005, Wenger et al. 2009). Subsequent dramatic changes to the composition of biotic assemblages of lotic systems in response to urbanization are well documented in fishes (Onorato et al. 2000, Walters et al. 2005, Meixler 2011) and macroinvertebrates (Roy et al. 2003, Wang and Kanehl 2003, Moore and Palmer 2005).

The Sudbury River is an example of a river in an urban landscape with a long history of competing demands for water resources. The river flows through suburban and urban neighborhoods on the outskirts of the Boston metropolitan area, one of the oldest cities in the United States. As such, the river has long been tapped for human uses. The river currently has numerous surface water and groundwater withdrawals and is considered to be stressed during periods of low flow (Zariello et al. 2010). Continued development in the river basin has prompted concerns about the impacts of future water withdrawals on the ecology of the river (Eggleston et al. 2012). The Sudbury River is a nationally designated wild and scenic river and is the focal point of the Great Meadows National Wildlife Refuge. A previous study modeled the potential hydrologic impacts of future groundwater withdrawals to summer baseflows (Eggleston et al. 2012). Although this study provided a detailed analysis of impacts to river water levels, it did not address potential impacts to river ecology.

The goal of this study was to investigate potential linkages between flow alteration, habitat availability, and ecological integrity in the Sudbury River adjacent to the Great Meadows National Wildlife Refuge. Specifically, we: 1) developed a species list for the Sudbury River based on field surveys of fishes, mussels, and macroinvertebrates, 2) determined habitat and flow requirements for fishes and mussels using existing literature, 3) quantified stream physical habitat characteristics within selected stream reaches in the Sudbury River, and 4) modeled effects of changes in stream flow on the quantity and quality of stream habitat features. The results will be useful for understanding past and potential future consequences of altered hydrology in the Sudbury River and informing management of other waterbodies that are threatened by flow alteration.

Methods

Sudbury River Basin Description

The Sudbury River begins in Great Cedar Swamp in Westborough, Massachusetts (MA) and then flows east through the towns of Hopkinton, Southborough, Ashland, and Framingham before traveling north through Sudbury, Wayland, and Lincoln, MA (Fig. 1). Total river length is approximately 46 km before the Sudbury joins with the Assabet River in the town of Concord to form the Concord River, which empties into the Merrimack River at Lowell, MA. The Sudbury is located in the coastal lowlands and has an average gradient of 0.98 m/km (Zariello et al. 2010). The basin lies east of Boston, MA and is part of the Boston metropolitan area.

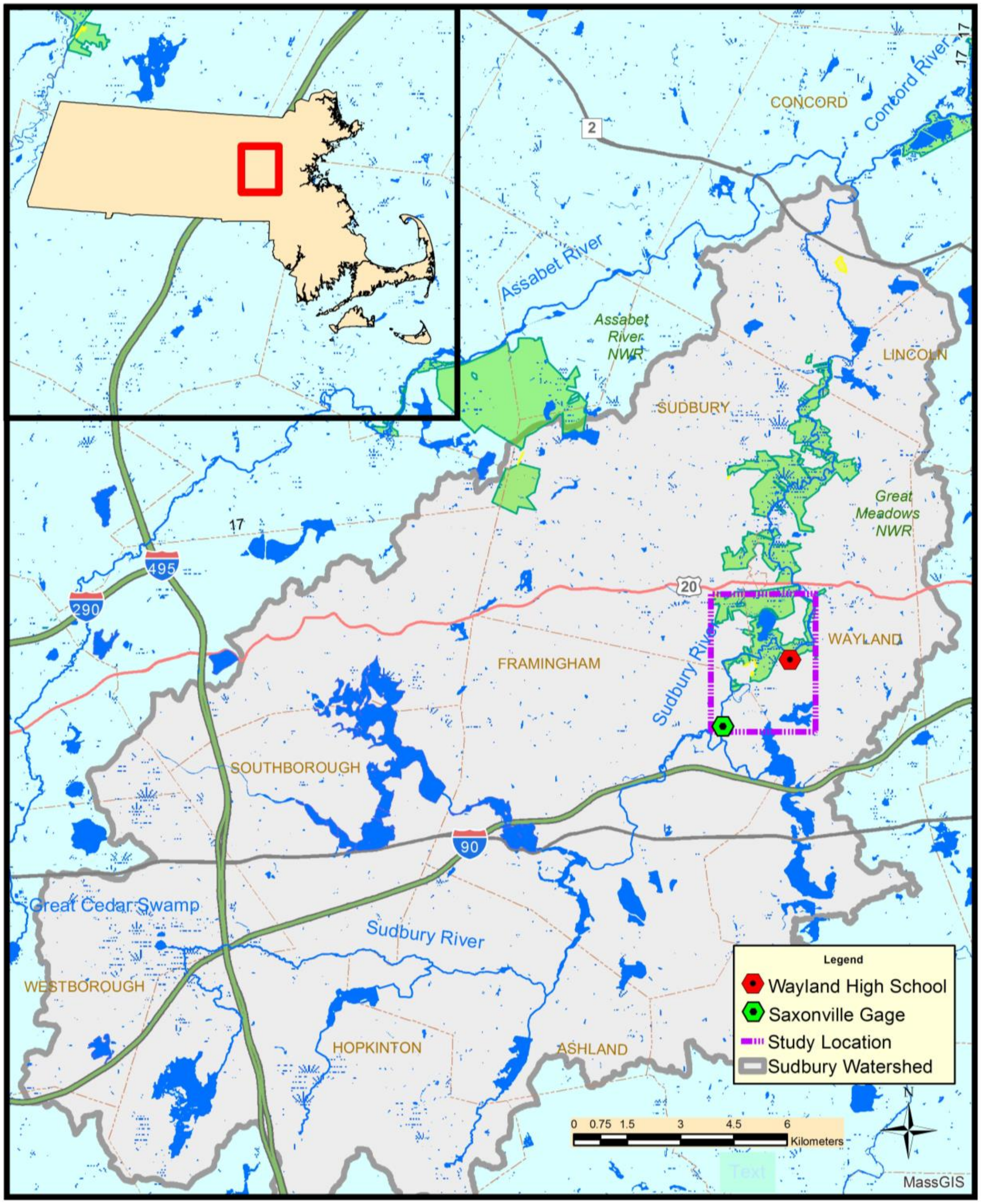

Figure 1 Regional map of the Sudbury River from the source at Great Cedar Swamp to the confluence with the Assabet River in Massachusetts, USA.

Dams appeared on the Sudbury River as early as the 18th century to power mills, but were subsequently repurposed for water supply and flood control. Currently, there are six dams on the mainstem of the Sudbury River (O'Brien-Clayton et al. 2005), located both upstream and downstream of the focal study area. Two of these are large impoundments controlled by the Metropolitan District Commission as reserve water supplies. These reservoirs were constructed in the late 1800s to supply water to Boston, but decreasing water quality and the construction of Quabbin reservoir in the 1930s and 1940s discontinued their use. In addition to these mainstem reservoirs, several tributaries have reservoirs that also originally served to supply water to Boston. These include Lake Cochituate on Cochituate Brook, Whitehall Reservoir on Whitehall Brook, and Reservoir Number Three (Foss) on Stoney Brook.

Monthly mean precipitation varies from 7.7 cm in February to 9.9 cm in November (Zariello et al. 2010). Mean annual snowfall is 177.8 cm, mostly falling in the period from December to March. Average January temperature is -4.6°C while average July temperature is 21.2°C with an annual mean of 8.3°C. Long term trends based on analysis of data from National Weather Service for the years 1892 to 2002 indicate that mean annual precipitation has increased by roughly 30% (Zariello et al. 2010).

There are a several known sources of impairment in the Sudbury River basin. The Sudbury watershed drains a suburban to urban area having a population of 185,200 in 2000 (Zariello et al 2010). Based on the 2011 USGS National Land Cover Database (NLCD) percent developed impervious layer, the watershed upstream of the Saxonville gage has 19.9% impervious surface cover. Over a 19-year period from 1992 to 2011, developed land (low, medium, and high intensity, and open space) increased from 30.4% to 46.4%, while forested land (deciduous, evergreen, and mixed forest, and forested wetlands) decreased from 51.9% to 42.2% over the same time (Figs. 2 and 3). A federal Superfund site in the town of Ashland (the Nyanza chemical waste dump) operated from 1917 to 1978 producing textile dyes and other products. During operation, over 45,000 tons of chemical sludge were buried (O'Brien-Clayton et al. 2005). This site is an ongoing source of mercury contamination that has resulted in an advisory against consumption of fish caught from the river (McKeon and McLaughlin 1991, Salazar et al. 1996). There are also several municipal storm sewers in the basin (O'Brien-Clayton et al. 2005).

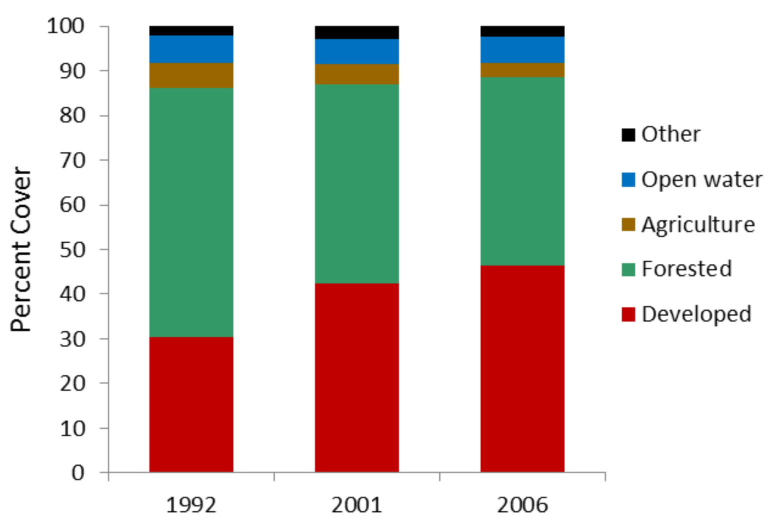

Figure 2 Land use/cover for the years 1992, 2001, and 2011 in the Sudbury River basin upstream of the USGS Saxonville gage.

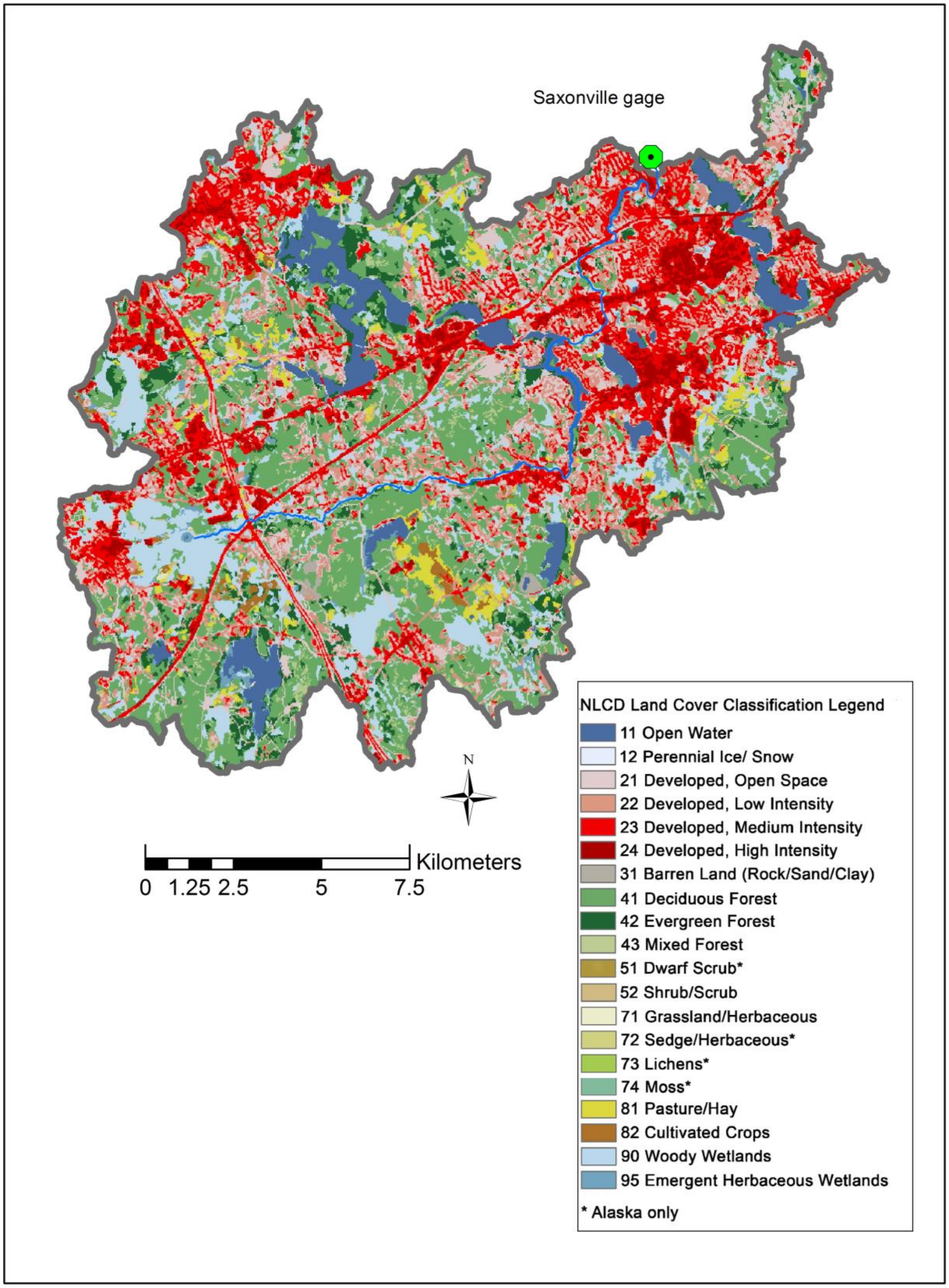

Figure 3 Land use/cover in the Sudbury River watershed upstream of the Saxonville gage for 2011.

Study Area

The study area for this report includes the 5 km segment below the U.S. Geological Survey's (USGS) Saxonville gaging station (01098530). Although the segment is free-flowing, there is a mainstem flood control dam upstream of the gage. Within the river segment, six reaches were selected for biotic and habitat surveys. Reaches were selected based on accessibility (Danforth Street, Little Farms Road, Old Stone Bridge), with additional reaches selected based on canoeing the entire river segment and selecting reaches that seemed to have suitable mussel habitat and were distributed throughout the study site (Figs. 4-6). The most upstream reach was located below the Danforth Street bridge while the most downstream reach was 5.32 km downstream of Danforth Street, adjacent to Wayland High School.

The segment of the Sudbury River in this study is a low gradient river with extensive wetlands surrounding the lower reaches. At the upstream end of the study site, elevation at the water surface is approximately 34.9 m above sea level while the elevation at the downstream end is approximately 33.5 m, a 1.4 m elevation drop over a channel distance of 5.32 km, or 0.26 m/km. Uplands in the basin are composed of glacial till while valleys are coarse and fine grained glacial deposits. These deposits average roughly 11 m thickness and are overlain by alluvial deposits along stream and river channels (Zariello et al. 2010).

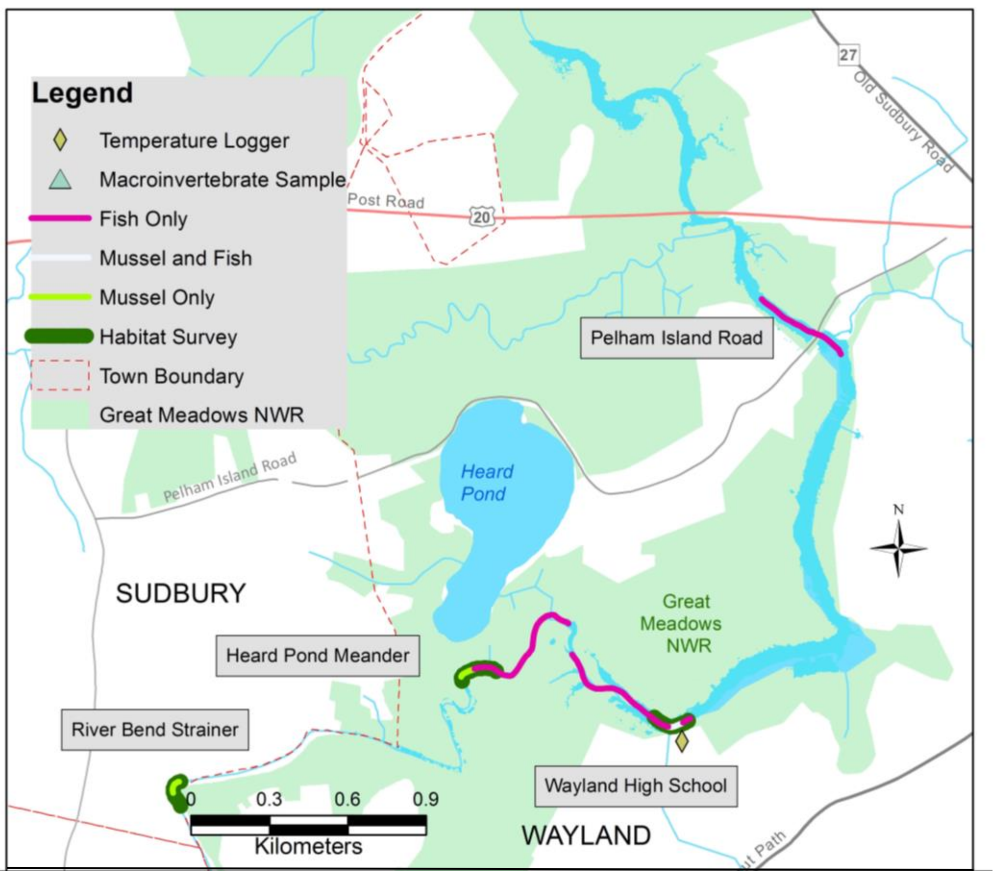

Figure 4 Downstream locations of biotic sampling sites and habitat surveys.

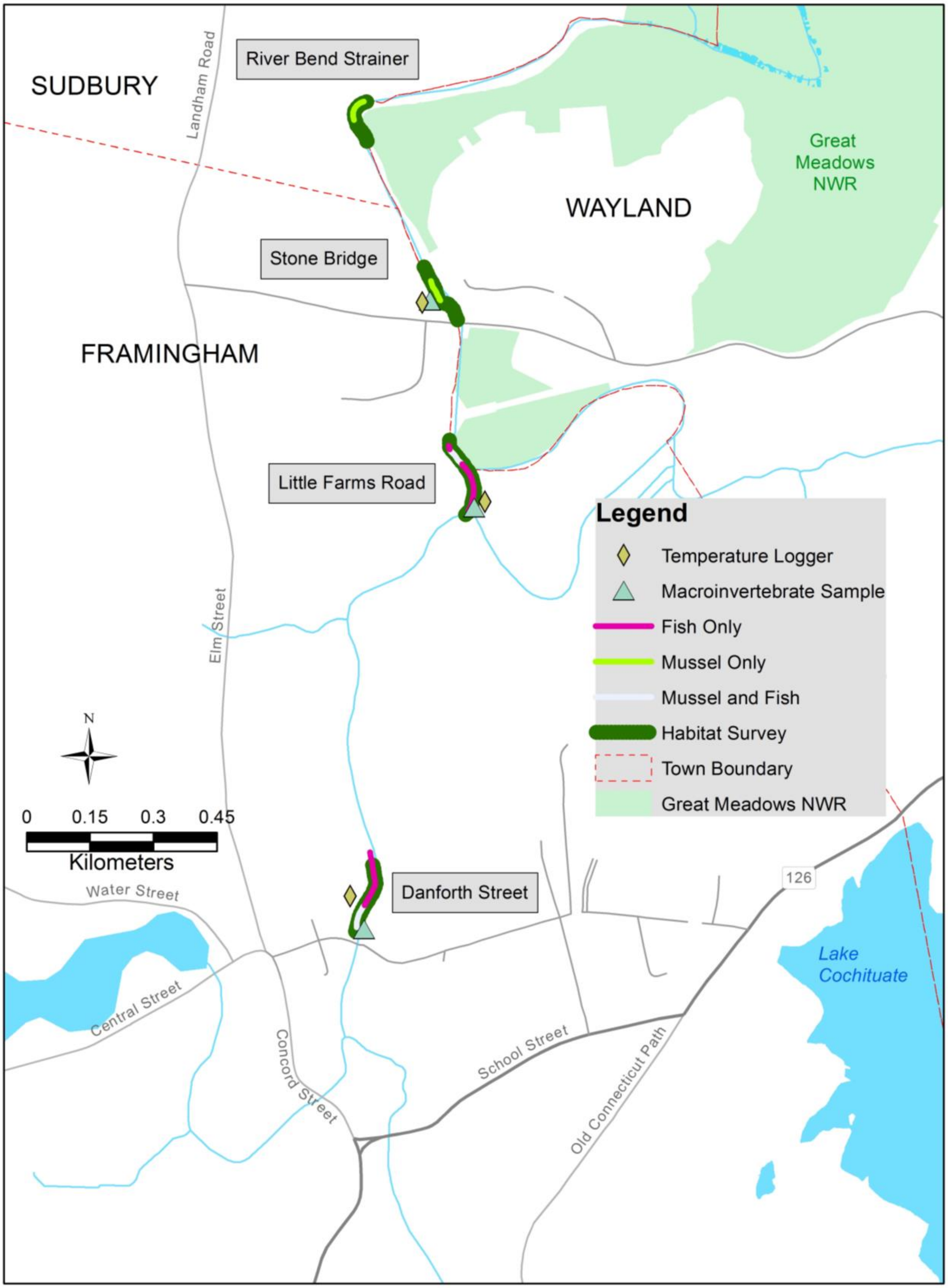

Figure 5 Upstream locations of mussel sampling sites and habitat surveys.

Figure 6 Photos of study reaches. From upper left to lower right a) Danforth Street b) Little Farms Road c) Stone Bridge d) River Bend Strainer e) Heard Pond Meander f) Wayland High School. All photos are looking upstream.

Macroinvertebrate Sampling

Benthic macroinvertebrates were collected on 12 August 2014 at the three reaches with riffle or riffle-run habitat: Danforth Street, Little Farms Road, and Stone Bridge (Fig. 5). We used a Surber sampler (500-µm mesh) to collect macroinvertebrates at three, haphazard locations within riffle habitats by disturbing substrate to ~10 cm for 1 min. Samples were composited for each site, elutriated, and preserved in 70% ethanol. Samples were sorted, identified to the lowest possible taxonomic level (typically species), and enumerated by Cole Ecological, Inc.

Mussel Sampling

Mussels were surveyed on 7 and 8 August 2014 during baseflow conditions. At each reach, a 50-m section was designated for timed visual survey (20-47 mins). A crew of six individuals began at the downstream end of the reach, spaced evenly along the river cross section. Three individuals snorkeled in the deeper areas, while three individuals used viewing buckets in the shallower areas. Crews collected live mussels working upstream through the reach. When sampling was completed, mussels were identified to species and enumerated (Fig. 7). Shell condition (1 = slightly eroded to 5 = extremely eroded), length, and sex (where determined) were also recorded. Mussels were returned to the reach when observations were completed.

Fish Sampling

Fish sampling was conducted on 12 and 19 August 2014 during baseflow conditions (higher discharge on 2 and 13-16 August 2014). The two upstream locations (Danforth Street and Little Farms Road) were sampled using a backpack electroshocker. At Danforth Street, a crew of nine people worked upstream using two backpack electroshockers and dip nets in a single pass, with a block net at the upstream end of the ~150-m reach. At Little Farms Road, a 158-m reach was sampled in a single, upstream pass with a crew of 6 people and two electroshockers. The downstream stretch of river was too deep for backpack electrofishing and was sampled using a boat electroshocker in areas accessible from the Route 20 bridge. This sampling included three reaches, each sampled with a single, 15-minute pass. All fish were identified to species, counted, and measured (total length) before being returned to the river.

Figure 7 Sorting and enumeration of sampled mussels. Mussels are Eastern elliptio (left) and Eastern lampmussel (right).

Macroinvertebrate Metrics

To summarize the macroinvertebrate assemblage, we calculated richness (no. taxa) and density (no. m^{-2}) for all taxa and insect taxa. We also calculated richness, density, and proportional density for the family Chironomidae (that includes many tolerant taxa), and the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT taxa, that includes many sensitive taxa). A biotic index was calculated based on genus and species-level pollution tolerance values reported by Klemm et al. (2002). Tolerance values range from 0 to 10, with intolerant taxa having tolerance values <4, and tolerant taxa having values >7 (Appendix A1). A cumulative biotic index score and associated water quality rating were reported.

Mussel and Fish Traits Synthesis

We identified traits for the fish and mussel species collected during the surveys to understand the characteristics of species that live in the Sudbury and infer how flow, habitat, temperature may be impacting species presence or abundance. Traits were determined based on published literature (Scott and Crossman 1973; Carlander 1977; Lee et al. 1980; Page 1983; Trial et al. 1983; Wismer and Christie 1987, Bogan 2002; Hartel et al. 2002; Swartz and Nedeau 2007, Bogan and Alderman 2008; Nedeau 2008; Nadeau and Victoria 2003, Doherty et al. 2010; Galbraith et al. 2012; NatureServe 2014; Warren and Burr 2014). Traits included those that could potentially be affected by flow alteration, including: current velocity preference, habitat type preference (e.g., lake, pond, river), and spawning strategy and habitat, following Taylor et al. (2013). Traits are summarized in Tables A3 and A6. We also summarized traits for fish species in the TFC (see below) that were not sampled (Table A4), and mussel species present in Massachusetts that were not sampled (Table A7) to consider factors that may have led to loss of species that may have been historically present in the Sudbury River.

Evaluation of Fish Community Using the Target Fish Community Model

The target fish community (TFC) model has been widely used in the Northeastern US as a robust method to quantify fish community response to disturbance (Legros and Parasiewicz 2007, Bain and Meixler 2008, Kashiwagi and Richards 2009, Meixler 2011). The TFC method compares the observed fish community for a river of interest to an expected target fish community based on sampling of relatively unimpacted rivers with similar physical and zoogeographic features, with 0 indicating no similarity and 100 indicating complete overlap. The deviation from this expected TFC can be used to make inferences about the degree of disturbance to a system. A TFC for the Concord River has been developed by the Massachusetts Division of Fisheries and Wildlife (Kashiwagi and Richards 2009). We compared the data from our Sudbury fish samples to this Concord River TFC using a similarity index as described in Novak and Bode (1992).

We also summarized the fish assemblage based on richness, density, and proportional density of species within each habitat category (macrohabitat generalists, fluvial dependents, and fluvial specialists) following Meixler (2011). Macrohabitat generalists are species that can be found in a wide range of habitats from lentic to lotic and that can complete their entire life history in either one. Fluvial dependents are species that may be found in many habitats, but that rely on lotic systems for at least one portion of their life history, such as spawning. Fluvial specialists are those species that are associated almost exclusively with lotic systems. Additionally, we classified fish species into pollution tolerance categories (intolerant, moderately tolerant, and tolerant) based on Meixler (2011).

Temperature Monitoring
Temperature loggers (Hobo® ProV2) were deployed from 12 August 2014 to 25 September 2015 at four locations: Danforth Street, Little Farms Road, Stone Bridge, and Wayland High School. Loggers were housed in a PVC case and anchored to a nearby tree with steel cable. The loggers were set to continuously record water temperature at 15 min intervals. Temperature data were compressed to daily data and summarized as monthly mean, minimum, and maximum values at each site.

Habitat Surveys
Habitat surveys were conducted in six, ~150-m reaches between 10 September and 1 October 2014. Reaches included each of the 50-m mussel sampling sites and overlapped with fish sampling sites when the fish sites encompassed the mussel sampling sites. At each site, electronic survey equipment (Leica® FlexLine Total Station 06 Plus) was used to survey (1) the wetted perimeter, (2) a longitudinal profile within the thalweg, and (3) at least three cross sections (Fig. 8). During surveying, habitat was classified into one of three types: riffle, run, or pool for each of the thalweg points in the longitudinal profile. Habitat was classified as riffle if flow appeared to be swift and turbulent with gravel, cobble, or boulders breaking the water surface. If velocity appeared to be swift, but flow was not turbulent, habitat was classified as run. Where velocity was sluggish, habitat was classified as pool. Generally, runs were <0.5-m deep; however, we did not make this an absolute rule as some locations had depths less than this but had minimal velocity. These evaluations were subjective evaluations, and transitional areas between runs and pools were often difficult to differentiate. Cross sections were selected to capture distinct habitat types or significant changes to channel morphology. Survey data collected using the electronic total station were used to generate maps of habitat at each reach using ArcGIS (version 10.2). Additionally, these data were used to generate graphical profiles of each cross section (20 cross sections total) using R version 3.1.1.

Pebble counts were conducted to characterize streambed texture at cross sections with shallow water. Fifty particles were measured and the median value was recorded. At each point used to delineate cross sections, depth and flow velocity were recorded. Canopy cover was quantified using a spherical densiometer at three locations (river right, center, and river left) in each cross section.

Figure 8 Conducting habitat surveys.

Characterization of River Flow

We used the Indicators of Hydrologic Alteration (IHA, the Nature Conservancy) software to characterize the contemporary hydrological regime in the river. This software generates a suite of variables related to the magnitude, timing, duration, frequency, and rate of change of flows that are intended to describe biologically-relevant flow variables (Richter et al. 1996, 1997, 1998). We used daily data from the entire Saxonville gage time series from 1981 to 2013 to calculate annual hydrologic metrics.

We graphed select metrics through time to identify trends in relevant indicator variables, and thus potential hydrologic alteration that has occurred during the record of the Saxonville gage. The IHA program generates a plot of environmental flow components through time. These components include low flows, extreme low flows, high-flow pulses, small floods, and large floods. In addition, we plotted annual 1-day minimum flow, annual high pulse count, annual rate of rise, annual extreme low flow frequency, annual median August flows, and annual median September flows. For each of these values, IHA uses linear regression to test for trends in these variables through time.

Modeling Water Surface Height and Habitat Types at Different Discharges

Simple hydrological models were used to model habitat (i.e., riffle, pool, run) availability as a function of streamflow. To obtain water surface height associated with discharge at each cross section, we first set up a linear equation relating cross-sectional area to discharge at each cross section using two known points. For the first known point, we used the observed cross sectional area at the time of surveying and associated discharge at the USGS Saxonville gage. For the second point we generated the cross-sectional area for the measured bankfull height during surveying and the discharge for a 1.8-year return interval flow (Leopold 1968) as determined by IHA software. To obtain cross sectional areas, we used the package PBSMapping (Schnute et al. 2013) in R version 3.1.1 (R Core Team 2014) to calculate the cross-sectional area at each surface height and then used PBSMapping to generate a matrix of cross-sectional areas for a range of surface heights at each cross section. Using this matrix and the discharge to area equations, we generated the change in water surface height relative to surface height at time of surveying for any given discharge at each cross section.

We selected three relevant discharges to use as targets for modeling surface height. For a representative low flow, we used the lowest flow available in the Saxonville record over the previous year (6.2 cfs; 0.18 cms), although gage records indicate that other years have experienced lower flows (3.6 cfs; 0.10 cms). For a median flow, we selected 10 cfs (0.28 cms), a discharge that was in the range of our observed flows (7.0–13.0 cfs; 0.20–0.37 cms), and approximated the flow during most of the surveying. For high flows, we used the median 30-day maximum flow generated by IHA analysis (31.6 cfs; 0.89 cms). We compared our range of variation in surface height at the cross section nearest to the Saxonville gage to actual variation in gage height for these same flows. We used the observed difference to generate a constant to use to multiply our relative differences by to arrive at our final estimates of surface height at each discharge.

We plotted the expected surface height at each of our target discharges, as well as the observed surface height at the time of total station surveys. For observed surface height, we used the wetted perimeter points from the longitudinal profile. In some cases downstream cross sections had expected surface heights higher than the upstream cross section. We assumed that in these cases, water would back up in the upstream section, raising the expected height while lowering the expected height at the downstream cross section. We adjusted these accordingly by raising the expected height in the upstream section while lowering the expected height in the downstream section. In most cases, these differences were 1–2 cm.

We used changes in water surface height to approximate proportional differences in habitat area at discharges lower (6.2 cfs; 0.18 cms) and higher (31.6 cfs; 0.89 cms) than the discharge during surveying. For this analysis, we focused on habitats classified as transitional locations that would be those most likely to change habitat types as discharge changed. We quantified our findings in terms of longitudinal length of stream habitat in the thalweg. For riffle habitats, we assumed that the relatively small decrease in discharge from the surveys (i.e., 7 to 9 cfs) to 6.2 cfs would not affect riffle habitat. At 31.6 cfs, we assumed that if depth increased enough to sufficiently submerge bed material, the riffle would likely transition to a run. We inferred shifts in pool and run habitat based on assumed changes in velocity and depth with changes in discharge. Studies have found that a good indicator metric to distinguish pool and run habitat is the velocity to depth ratio, where for any given depth, increasing velocity will favor run habitat (Jowett 1993). Therefore, we reasoned that if the proportional decrease in discharge exceeded the proportional decrease in area for a cross section, velocity would decrease and habitat would be classified as pool. In contrast, if the proportional decrease in area for a cross section exceeded the proportional decrease in discharge, velocity would increase and habitat would be classified as run. The opposite habitat transitions would be true for proportional increases in discharge.

Results

Macroinvertebrates

Overall, 56 macroinvertebrate taxa were collected, including 39 insect taxa (Tables 1, A1). Chironomidae was the most diverse family with 20 unique taxa. Average macroinvertebrate density was 3752 ind. m^{-2}, although densities ranged widely among reaches, with 6956 ind. m^{-2} at Little Farms Road and 1651 ind. m^{-2} at Stone Bridge (Table 1). The majority (61%) of individuals collected were from Ephemeroptera, Plecoptera, and Trichoptera (EPT)— orders primarily dominated by taxa sensitive to disturbance; however, the EPT taxa collected in this study were generally tolerant. The three numerically dominant EPT taxa were *Chimarra obscura* (Trichoptera: Philopotamidae), *Cheumatopsyche* sp., and *Hydropsyche betteni* (Trichoptera: Hydropsychidae) that have pollution tolerance values of 4.0 (*Chimarra* sp.), 5.5, and 5.7, respectively (potential range 0-10, with 10 being most tolerant; Klemm et al. 2002). No taxa in the sensitive order Plecoptera were sampled. Generally-speaking, EPT richness was low, with 8–10 taxa represented at each of the three reaches, and 12 taxa overall.

Overall biotic index scores ranged from 4.9 (good) to 6.0 (fair) across the four sites. There were generally low proportional abundances of tolerant taxa, except at Stone Bridge with 31.2% tolerant. There were very low proportions of intolerant taxa at all sites (Table 1).

Table 1 Macroinvertebrate richness, density, and proportional density at three sites. EPT = Orders Ephemeroptera, Plecoptera, and Trichoptera.

Metric	Danforth	Little Farms	Stone Bridge	Overall
Richness (no. taxa)				
Total	31	29	41	56
Insecta	24	23	25	39
EPT	8	9	10	12
Chironomidae	13	12	10	20
Density (no. m^{-2})				
Total	2650	6956	1651	3752
Insecta	1846	6622	333	2934
EPT	1453	5244	201	2299
Chironomidae	350	1133	95	526
Proportional Density (%)				
Insecta	69.7	95.2	20.2	78.2
EPT	54.8	75.4	12.2	61.3
Chironomidae	13.2	16.3	5.8	14.0
Biotic Index				
Biotic Index score	5.1	4.9	6.0	5.3
Biotic Index rating	Good	Good	Fair	Good
Tolerant (%)	1.4	4.2	31.2	12.3
Intolerant (%)	0.7	4.5	3.1	2.8

Mussels

Five species of mussels were sampled (Figs. 9 and A1; Tables 2 and A2). Eastern elliptio (*Elliptio complanata*; Fig. 9A) and Eastern lampmussel (*Lampsilis radiata*; Fig. 9C) were the most abundant species sampled, comprising 58.3% and 40.0% of the total number of individuals, respectively. One species of special concern in Massachusetts, Eastern pondmussel (*Ligumia nasuta*; Fig. 9B), was collected (six individuals) at Danforth Street and Little Farms Road.

All the sampled mussel species are generalists that may be found in a wide range of habitats from lentic to lotic (Table A3). These mussels do not have strong preferences for particular substrate types or current velocities. All the mussels sampled have several fish hosts, and the species include those that are prevalent in the Sudbury. There are 7 species of mussels that are found in Massachusetts but were not sampled in the Sudbury. The cool temperature requirements (Eastern pearlshell), moderate to fast velocities (brook floater, dwarf wedgemussel), and requirements for host fish such as salmonids and alewife that are no longer in the Sudbury (Eastern pearlshell, dwarf wedgemussel, alewife floater) may be preventing these mussels from inhabiting the Sudbury (Table A4).

Figure 9 Examples of sampled mussel species: A) Eastern elliptio, one having deformity (left) B) Eastern pondmussel C) Eastern lampmussel, male and female, and D) triangle floater. Photos courtesy of Peter Hazelton, MDFW-NHESP.

Table 2 Mussel species sampled at each stream reach. Reaches are ordered from upstream to downstream.

Site	Km downstream from Danforth Street	***Elliptio complanata*** Eastern elliptio	***Ligumia nasuta*** Eastern pondmussel	***Lampsilis radiata*** Eastern lampmussel	***Pyganodon cataracta*** Eastern floater	***Alasmidonta undulata*** Triangle floater
Danforth Street	0	263	3	206	1	2
Little Farms Road	1.16	34	3	42		
Stone Bridge	1.64	31		11		
River Bend Strainer	2.16	9		5	1	
Heard Pond Meander	3.97	77		27		1
Wayland High School	5.32	10			1	
Total		424	6	291	3	3

Fishes

A total of 816 individuals of 17 species of fish were sampled (Table A5). The fish assemblage was dominated by bluegill (*Lepomis machrochirus*, 43.4%), yellow perch (*Perca flavescens*,18.2%), American eel (*Anguilla rostrata* 8.4%), white sucker (*Catostomus commersoni*, 6.7%), and largemouth bass (*Micropterus salmoides*, 5.7%) (Table A5). Two of these species (bluegill and largemouth bass) are introduced species that are not in the TFC. Fallfish (*Semotilus corporalis*, 2.7%), a fluvial specialist, and white sucker, a fluvial dependent species, were the only fluvial species found in the surveys. Fallfish, the species expected to be most common according to the TFC, only comprised 2.7% of the observed community, and these were found primarily near the riffle at Little Farms Road. Several species in the TFC were absent from the observed community, including common shiner, tessellated darter, bridle shiner, brook trout, and creek chubsucker (Table 3). We also sampled seven species that were not present in the TFC. Our sample and the TFC had a similarity score of 22.7.

Across all sites, the fish community was dominated by macrohabitat generalists (90.6%), which contrasted sharply with the TFC (25%, Fig. 10). Out of four fluvial specialist species present in the TFC, only fallfish were sampled, but they only comprised a small proportion of the sampled individuals (2.7%; 22 individuals) compared to the TFC (48%). In terms of pollution tolerance, the fish community was composed of tolerant (65.1%) and moderately tolerant (34.9%) individuals (Fig. 11). Of three intolerant species present in the TFC (brook trout, bridle shiner, and creek chubsucker), none were sampled. In contrast, expected proportions in the TFC are 17.1% tolerant, 75.4% moderately tolerant, and 7.7 % intolerant.

The fish species sampled had traits that were aligned with low-gradient rivers (Table A6). With the exception of fallfish and white suckers that are gravel spawners, all other fish species are able to spawn in sandy substrate or vegetation, which is prevalent throughout the Sudbury. Several Centrarchids (e.g., pumpkinseed, redbreast sunfish, rock bass) prefer rocky habitats, but more essentially require slow-moving water with vegetative cover, which is characteristic of the Sudbury. Fallfish, particularly juveniles, are the only captured fish that requires higher velocities with rock and gravel substrates. The fish species currently in the Sudbury are tolerant of warm temperatures, with the exception of fallfish which are mostly found in water <28°C (Table A6). The species that were expected based on the TFC and were not captured had trait preferences that included gravel habitat for spawning (brook trout, common shiner, creek chubsucker), cool or cold temperatures (brook trout), and flowing water habitat (brook trout, common shiner, tessellated darter) (Table A7).

Table 3 Comparison of the target fish community with species sampled from the Sudbury River. Rows highlighted in orange represent species sampled that are not in the target fish community. Rows highlighted in green represent species in the target fish community that were not sampled from the river.

Species	TFC Proportion	Observed Proportion	Origin	Habitat-Use Category	Tolerance
American eel	4.1	8.4	N	MG	T
Black crappie	-	1.1	I	MG	M
Bluegill	-	43.3	I	MG	T
Bridle shiner	2.9	-	N	MG	I
Brook trout	3.4	-	N	FS	I
Brown bullhead	2.1	0.1	N	MG	T
Chain pickerel	2.3	0.6	N	MG	M
Common carp	-	0.7	I	MG	T
Common shiner	18.7	-	N	FD	M
Creek chubsucker	1.4	-	N	FS	I
Fallfish	37.3	2.7	N	FS	M
Golden shiner	1.6	4.5	N	MG	T
Largemouth bass	-	5.7	I	MG	M
Pumpkinseed	2.5	3.0	N	MG	M
Redbreast sunfish	6.2	1.5	N	MG	M
Redfin pickerel	2	0.2	N	MG	M
Rock bass	-	0.1	I	MG	M
Spottail shiner	-	1.7	N	MG	M
Tesselated darter	3.7	-	N	FS	M
White sucker	9.3	6.7	N	FD	T
Yellow bullhead	-	1.1	I	MG	T
Yellow perch	2.7	18.2	N	MG	M

Origin: N = Native, I = Introduced
Habitat-Use Category: FS = Fluvial Specialist, FD = Fluvial Dependent, MG = Macrohabitat Generalist
Tolerance: T = Tolerant, M = Moderately Tolerant, I = Intolerant

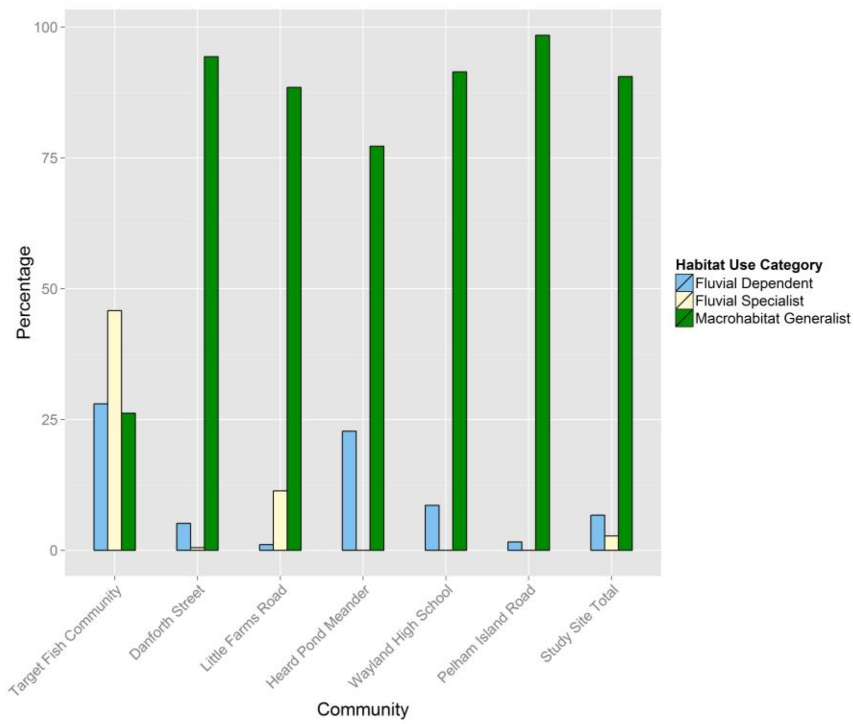

Figure 10 Fish assemblages at each site based on habitat preferences. The target fish community (TFC) is also included.

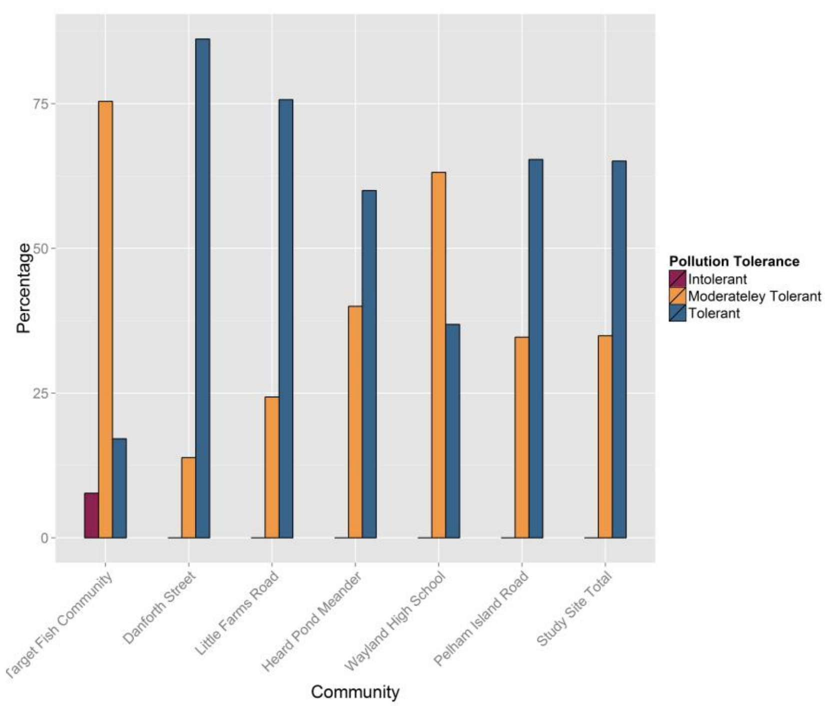

Figure 11 Fish assemblages at each site based on pollution tolerance. The target fish community (TFC) is also included.

Temperature

Stream temperatures were highest in July and August, averaging between 23.3° (Aug, Danforth) and 24.3° (July, Wayland) (Fig. 12). Maximum monthly temperatures were over two degrees higher in Wayland (>30°C) compared to the other sites (<28°C) in July and August. In September 2014, there was a much larger range in temperatures at Wayland High School compared to the other sites, which may be attributed to the logger being out of water.

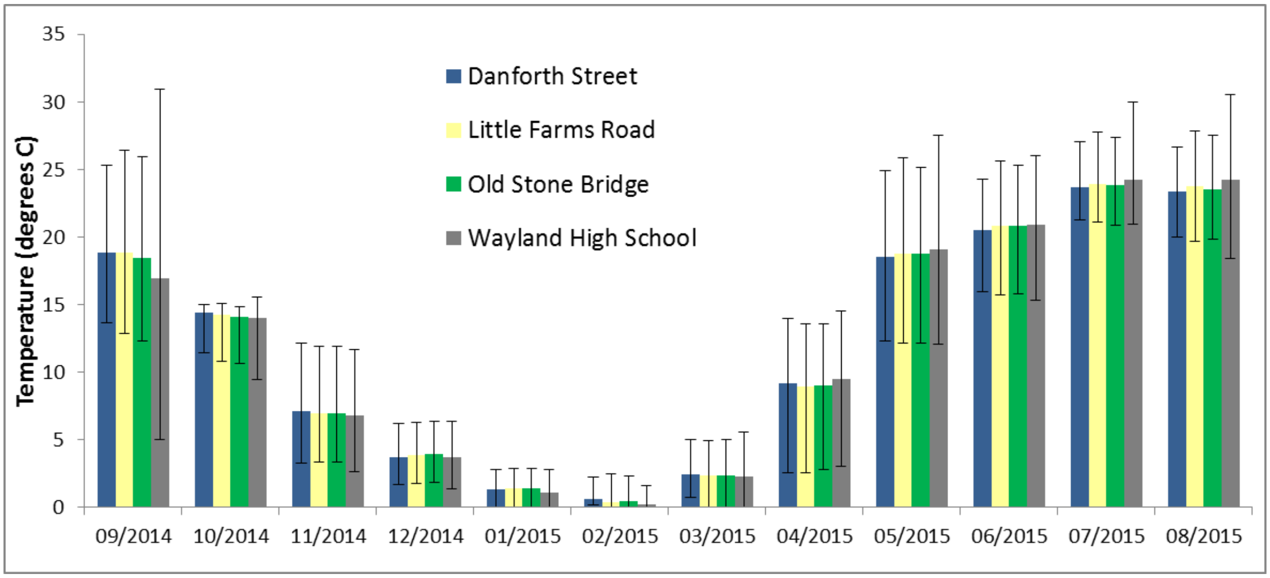

Figure 12 Mean and range (monthly min and max represented by error bars) of monthly temperatures at four sites.

Habitat Surveys

Overall, proportions of stream length were 2.9% riffle, 52.8% run, and 44.3% pool, but habitat types varied by site (Table 4, Figs. A2–A13). Median particle size at cross sections varied from 73 mm at the Little Farms Road riffle to silt at all the Wayland High School cross sections (Table 4). Velocities varied among cross sections based on habitat type, with the highest mean velocities at the riffle and run at Little Farms Road (cross sections 4 and 6) and the riffle at Danforth Street (cross section 1), and mean velocities less than 0.075 m^3s^{-1} at all other cross sections (Table 5). Mean water depths within cross sections at time of sampling ranged from 0.08 m at the riffle at Little Farms Road to 0.70 m at the River Bend strainer (cross section 12; Table 5). Canopy cover also varied among cross sections and sites, with the Wayland High School site having the lowest canopy cover (Table 6).

Table 4 Length of riffle, run, and pool habitat by study reach.

Site	Riffle (m)	Run (m)	Pool (m)	Site Total length (m)
Danforth Street	5.6	97.0	54.1	156.7
Little Farms Road	22.0	62.9	110.9	195.8
Stone Bridge	0	141.5	14.0	155.5
River Bend Strainer	0	0	118.2	118.2
Heard Pond Meander	0	44.6	124.4	169
Wayland High School	0	156	0	156
Overall Total Length (m)	27.6	502.0	421.6	951.2
Percentage of Total Length	**2.9%**	**52.8%**	**44.3%**	

Table 5 Mean and range of velocities and water depths at surveyed cross-sectional points.

				Velocity (m^3s^{-1})			Depth (m)		
Site	**Cross Section #**	**Habitat**	**# Points**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Danforth Street	1	Riffle	7	0.159	0.048	0.340	0.09	0.06	0.12
	2	Pool	7	0.028	0.002	0.064	0.54	0.08	0.94
	3	Run	8	0.065	0.000	0.110	0.18	0.06	0.31
Little Farms Road	4	Riffle	15	0.258	0.000	0.765	0.08	0.02	0.18
	5	Pool	14	0.042	0.000	0.088	0.39	0.08	0.92
	6	Run	6	0.118	0.000	0.297	0.21	0.06	0.54
	7	Run	9	0.046	-0.012	0.158	0.36	0.16	0.52
Stone Bridge	8	Run	16	0.027	-0.021	0.092	0.45	0.06	0.68
	9	Run	11	0.072	0.000	0.173	0.33	0.21	0.45
	10	Run	21	0.013	-0.023	0.091	0.42	0.00	0.79
River Bend Strainer	11	Pool	14	0.016	0.000	0.042	0.50	0.15	0.87
	12	Pool	14	-0.102	-1.603	0.068	0.70	0.22	1.02
	13	Pool	15	0.011	-0.008	0.029	0.65	0.20	0.89
Heard Pond Meander	14	Pool	12	0.032	-0.028	0.119	0.48	0.11	0.77
	15	Run	7	0.122	-0.071	0.331	0.19	0.09	0.25
	16	Pool	16	0.042	0.000	0.100	0.39	0.18	0.54
	17	Pool	23	0.044	0.018	0.066	0.61	0.22	1.00
Wayland High School	18	Run	29	0.061	0.000	0.102	0.17	0.04	0.31
	19	Run	34	0.041	0.000	0.109	0.21	0.08	0.31
	20	Run	31	0.069	0.000	0.151	0.24	0.11	0.47

Table 6 Habitat characteristics at cross sections for each habitat survey location. Cross sections appear from upstream to downstream going from top to bottom. Canopy refers to percent of densiometer surface reflecting leaf or other vegetation.

Site	Cross Section # (Habitat Type)	Median Particle Size	River Right Canopy	Midchannel Canopy	River Left Canopy	Comment
Danforth Street	CS 1 Riffle	37	78%	45.5%	92.2%	
	CS 2 Pool	38.5	70.6%	72.1%	94.1%	
	CS 3 Run	Sand	85.3%	51.5%	30.9%	
Little Farms Road	CS 4 Riffle	73	70.6%	23.5%	95.6%	
	CS 5 Pool	NA	25%	77.9%	100%	
	CS 6 Run	Sand	1.5%	1.5%	0%	
	CS 7 Run	Sand	72.1%	39.7%	72.1%	
Stone Bridge	CS 8 Run	NA	98.5%	14.7%	8.8%	Top and bottom runs had pool like characteristics. Slow currents
	CS 9 Run	30.5	16.2%	42.6%	52.9%	
	CS 10 Run	NA	50%	5.9%	50%	
River Bend Strainer	CS 11 Pool	Sand	86.8%	45.6%	48.5%	Top two pool sections had run like characteristics
	CS 12 Pool	Sand	10.3%	4.4%	0%	
	CS 13 Pool	NA	39.7%	55.9%	89.7%	
Heard Pond Meander	CS 14 Pool	NA	88.2%	77.9%	88.2%	
	CS 15 Run	23	97.1%	97.1%	94.1%	
	CS 16 Pool	13.5	27.9%	64.7%	89.7%	
	CS 17 Pool	Silt	0%	2.9%	8.8%	
Wayland High School	CS 18 Run	Silt	0%	0%	0%	Continuous, slow run would describe this section
	CS 19 Run	Silt	1.5%	0%	0%	
	CS 20 Run	Silt	4.4%	1.5%	0%	

Water Surface Height and Habitat Types at Different Discharges

The relationships between discharge and cross-sectional area at surveyed water level and bankfull (Table 7) were used to map water surface height at each of the target discharges (Figs. 13 and 14). Overall changes to surface height were relatively small, with most sites seeing at most an 8 cm rise at the 31.6 cfs discharge compared to survey conditions (7–13 cfs, depending on the date). Some narrower channel sections saw increases of about 16 cm. Decreases in height at the 6.2 cfs discharge were generally 2 cm or less. These changes in water levels corresponded to changes in habitat types.

At a reduced discharge of 6.2 cfs, we estimated no change to riffle habitat, a decrease in run habitat from 52.8% to 45.4%, and an increase in pool habitat from 44.3% to 51.7% compared to the surveyed conditions (Table 8; Figs. A14 and A15). At an increased discharge of 31.6 cfs, we predicted a decrease in riffle habitat from 2.9% to 2.31%, an increase in run habitat from 52.78% to 59.65%, and a decrease in pool habitat from 44.32% to 38.04% (Table 8; Figs. A14 and A15).

Table 7 Flow area relationships for each cross section based on discharge (x) and cross-sectional area (y) for wetted area and bankfull area determined during surveying. Relationships were used to generate water surface height at each discharge for each cross-section.

Site	Cross Section #	Flow Area Relationship	Surveying Date	USGS Gage Discharge at Surveying (cfs)	Wetted Cross-Sectional Area (m^2)	Bankfull Discharge (cfs, modelled)	Bankfull Cross-Sectional Area (m^2)
Danforth Street	1	y=0.0227x+0.7337	9/10/2014	9.2	0.9	960	22.5
	2	y=0.032x+10.614	9/10/2014	9.2	10.9	960	41.3
	3	y=0.0416x+2.5305	9/10/2014	9.2	2.9	960	42.5
Little Farms Road	4	y=0.0164x+0.9033	9/17/2014	13.0	1.1	960	16.7
	5	y=0.025x+5.0446	9/17/2014	13.0	5.4	960	29.0
	6	y=0.0244x+1.0132	9/17/2014	13.0	1.3	960	24.5
	7	y=0.0143x+5.444	10/1/2014	7.0	5.5	960	19.2
Stone Bridge	8	y=0.0172x+8.2332	9/23/2014	9.2	9.4	960	24.7
	9	y=0.0205x+2.4107	9/23/2014	9.2	2.6	960	22.1
	10	y=0.0369x+7.1913	9/23/2014	9.2	7.5	960	42.6
River Bend Strainer	11	y=0.0246x+8.5786	9/25/2014	8.0	8.8	960	32.2
	12	y=0.0258x+12.338	9/25/2014	8.0	12.5	960	37.1
	13	y=0.0145x+9.3617	9/25/2014	8.0	9.5	960	23.3
Heard Pond Meander	14	y=0.0094x+4.1654	9/29/2014	8.0	4.2	960	13.2
	15	y=0.0088x+1.0113	9/29/2014	8.0	1.1	960	9.5
	16	y=0.0099x+3.9422	9/29/2014	8.0	4.0	960	13.4
	17	y=0.0136x+6.2011	10/14/2014	7.0	6.3	960	19.2
Wayland High School	18	y=0.0289x+1.8469	9/12/2014	9.2	2.1	960	29.6
	19	y=0.0189x+2.5844	9/12/2014	9.2	2.8	960	20.8
	20	y=0.0127x+2.3772	9/12/2014	9.2	2.5	960	14.5

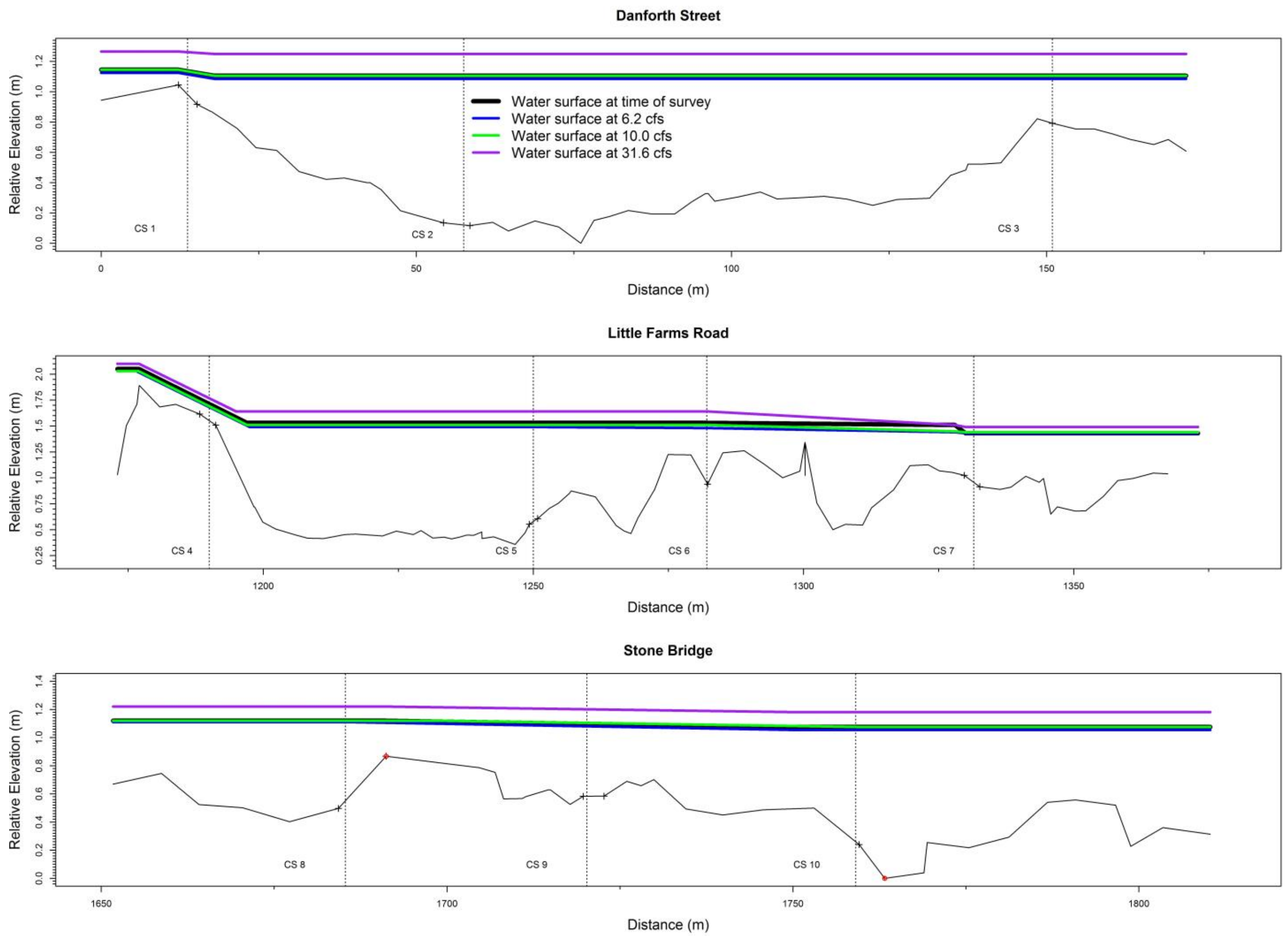

Figure 13 Longitudinal profile of thalweg at three survey sites with observed and modeled water surface at different flows. Dashed vertical lines represent the location of cross sections. Flows at time of survey were: Danforth Street, 9.2 cfs; Little Farms Road, 13 cfs (7 cfs at CS7); Stone Bridge, 9.2 cfs.

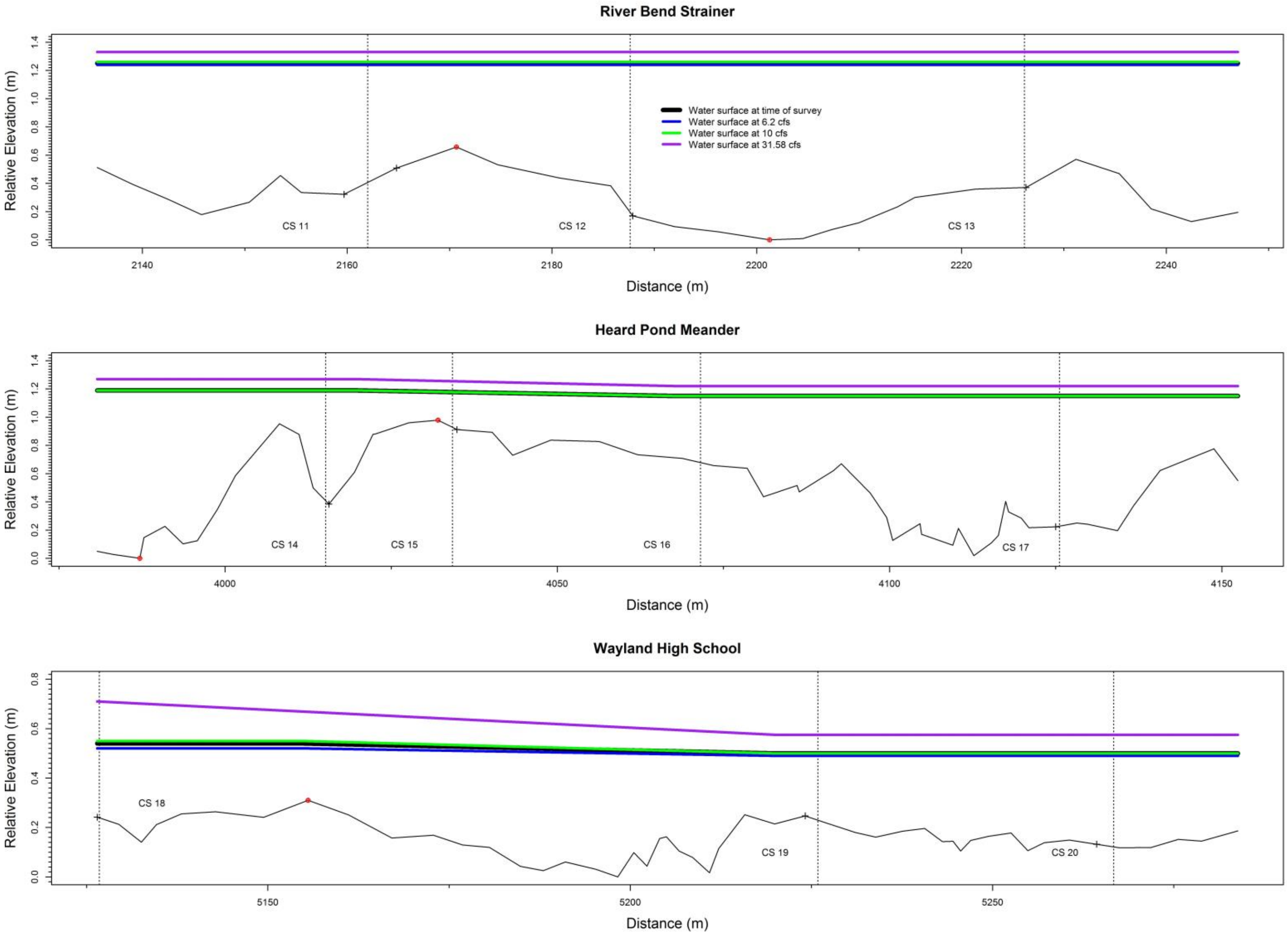

Figure 14 Longitudinal profile of thalweg at three survey sites with observed and modeled water surface at different flows. Dashed vertical lines represent the location of cross sections. Flows at time of survey were: River Bend Strainer, 8.0 cfs; Little Farms Road, 8.0 cfs (7 cfs at CS17); Wayland High School, 9.2 cfs

Table 8 Estimated longitudinal length of habitat types at three different discharges. Survey represents the observed discharge at time of habitat surveying. The other two discharges are modeled discharges and habitat at these discharges was determined by modeling.

Site	Riffle (m)			Run (m)			Pool (m)			Site Length Total (m)
	6.2 cfs	Survey	31.6 cfs	6.2 cfs	Survey	31.6 cfs	6.2 cfs	Survey	31.6 cfs	
Danforth Street	5.6	5.6	0	97	97	102.6	54.1	54.1	54.1	156.7
Little Farms Road	22	22	22	47.9	62.9	87.7	125.9	110.9	86.1	195.8
Stone Bridge	0	0	0	101.5	141.5	155.5	54	14	0	155.5
River Bend Strainer	0	0	0	0	0	0	118.2	118.2	118.2	118.2
Heard Pond Meander	0	0	0	29.6	44.6	65.6	139.4	124.4	103.4	169.0
Wayland High School	0	0	0	156	156	156	0	0	0	156.0
Overall Total Length (m)	27.6	27.6	22	432	502	567.4	491.6	421.6	361.8	951.2
Percentage of Total Length	2.9%	2.9%	2.3%	45.4%	52.8%	59.7%	51.7%	44.3%	38.0%	

Characterization of River Flow

Overall mean annual flow was 207.2 cfs (5.87 cms), with a range of daily flow from 3.6 to 2440 cfs (0.10 to 69.09) for the 33-year period. The IHA analysis indicates that lower flows were dominant from the months of July through October, with the lowest median monthly flow (40.0 cfs; 1.13 cms) in September (Table A8). Flows began to increase in November and were highest in March (monthly median 316.0 cfs; 8.95 cms), concurrent with spring snow melt. Median minimum flows were 32.4 cfs (30 day), 14.7 cfs (7 day), and 11 cfs (1 day). Median maximum flows were 565 cfs (30 day), 856.9 cfs (7 day), and 977.0 cfs (1 day).

When analyzing annual flow metrics over the 33-year period, we observed a trend of increasing variation in flows through time, with increases in both small floods and extreme low flows (Fig. 15, A16, A17). High pulse count showed an increasing trend, though this is not significant ($p = 0.10$) (Fig. 16). Rise rates increased roughly 200% through the 33 years (Fig. 16). One-day minimum flows decreased over the period, with current low flows reduced roughly 65% from those at the start of the period (Fig. 16). Extreme low flow frequency increased of roughly 180% from the start of the period (Fig. 17). There was no change in August and September median flows over the time period (Fig. 17).

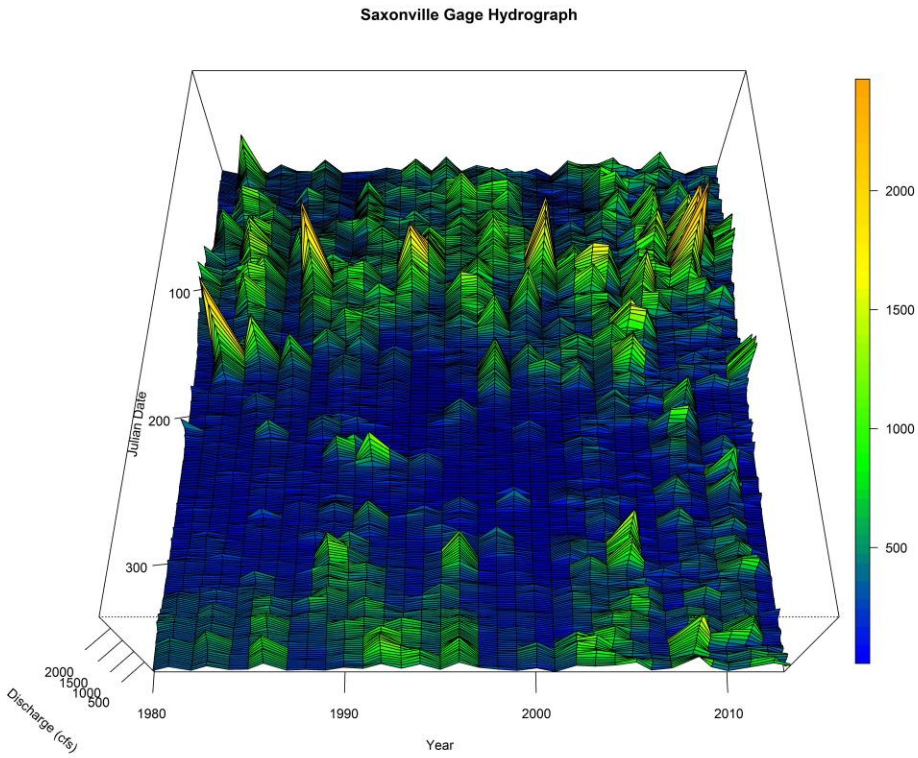

Figure 15 Hydrograph of Saxonville gage data. Julian date represents number of days following the first of the year.

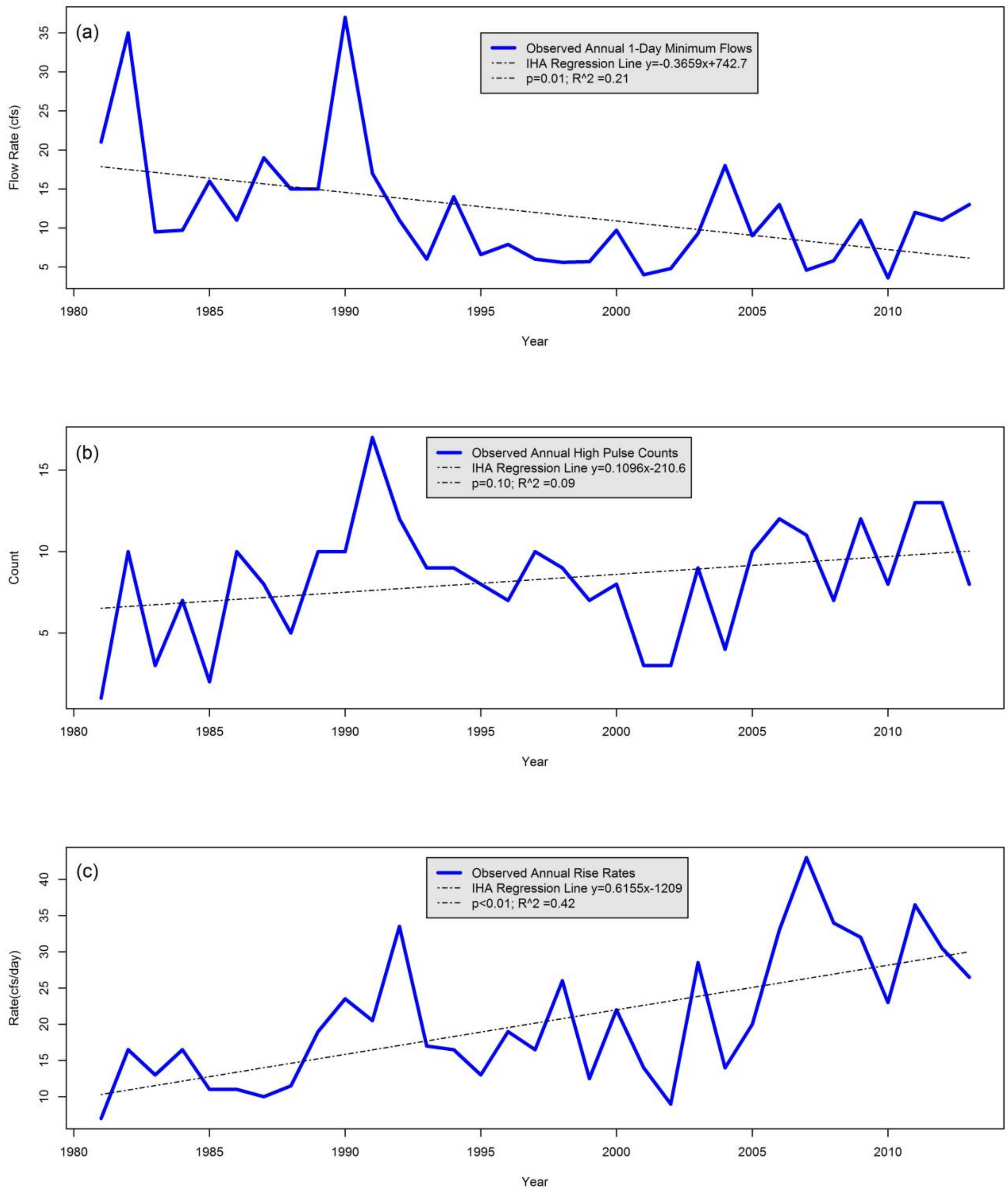

Figure 16 Annual a) 1-day minimum flows b) high pulse counts and c) rise rates over time based on the Saxonville gage data. Fitted regression lines are plotted over the observed data.

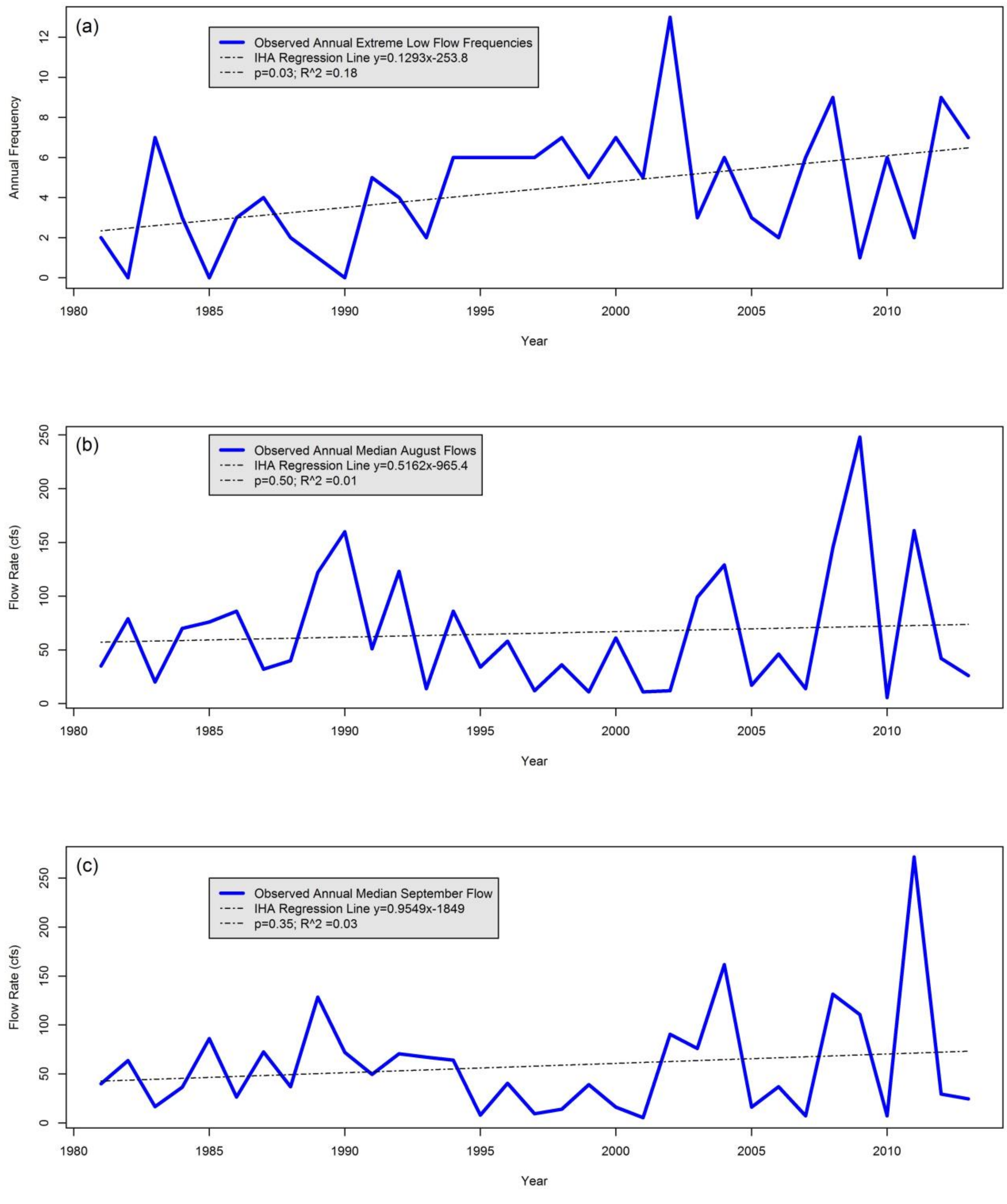

Figure 17 Annual a) extreme low flow frequencies b) median August flow and c) median September flow over time based on the Saxonville gage data. Fitted regression lines are plotted over the observed data.

Discussion

Hydrologic Alteration and Biotic Assemblages

There is a long-term history of human-induced flow alteration in the Sudbury that likely explains the current dominance by generalist mussel and fish species. Impoundments were built in the Sudbury River starting in the 1700s to power mills, and several reservoirs in the system were used as a water supply for the city of Boston beginning in the late 1800s (Zariello et al. 2010). Additionally, impervious surface area in the basin (19.9%) is above levels that begin to impact hydrology (Roy et al. 2005) and ecosystem integrity (Schueler et al. 2009), and it is likely that land use has affected the system for some time. Disruptions to the natural flow regime of a system can adversely impact native fish species and favor the establishment of introduced species and habitat generalists (Poff and Allan 1995, Moyle and Light 1996, Freeman and Marcinek 2006, Olden et al. 2006). Changes to hydrologic variability (Bain et al. 1988, Bunn and Arthington 2002) and extended periods of low flows (Roy et al. 2005, Freeman and Marcinek 2006) frequently favor fish macrohabitat generalists. The only fluvial specialist fish species (of four that were in the TFC) that was collected in our samples was the fallfish, and this was in much lower abundances than expected. Similarly, mussel species sampled were all generalist species found in a wide range of habitats (Nedeau 2008), and notably missing were the Eastern pearlshell and Eastern brook floater are species that are dependent on lotic habitats (Table A4) and have been previously reported in the Sudbury-Assabet-Concord basin. Mussels are particularly sensitive to low flows where individuals become stranded or population connectivity is lost (Peterson et al. 2011, Shea et al. 2013). Given the history of hydrologic alteration in the Sudbury, it seems likely that the loss of fluvial specialist species in the Sudbury began long before the current record of hydrological alteration.

The analysis of the 33-year period of stream gaging data indicates that streamflow characteristics have shifted between 1981 and 2013. Low flows are getting lower, extreme low flow counts are increasing, rise rates are increasing, and there is a trend towards increasing numbers of high flows. There are several potential explanations for these trends, including increasing water withdrawals, changes in weather patterns, changes to release practices at upstream dams, and changes to land use patterns. It is likely that a combination of factors is contributing to the current patterns. The Concord River basin is experiencing increased urbanization that has resulted in plans to refurbish several dams that were not designed to handle the resulting increased flood discharges (NRCS 2011). Increasing rise and fall rates and increased frequency of high flows are associated with increased catchment urbanization (Konrad and Booth 2005, Roy et al. 2005, DeGasperi et al. 2009). Increased runoff from impervious surfaces and decreased groundwater recharge can also result in decreased low flows (Leopold 1968, Bovee 1982, Konrad and Booth 2005), although this is not a universal response (Price 2011, Hamel et al. 2013). Based on the observed patterns and the contemporary changes in land use in the Sudbury, it is likely that urbanization has and continues to contribute to hydrologic alteration.

Additional Drivers of Biotic Impairment

Other factors such as temperature, water quality, and habitat quality may be important drivers of the biotic assemblages in the Sudbury. Brook trout were not found in the Sudbury River, although they are included the TFC for the Sudbury (Kashiwagi and Richards 2009). Brook trout are highly impacted by thermal regime and do not tolerate extended periods above 20°C (Hartel et al. 2002). All the sites sampled had mean monthly temperatures above 20°C for June, July, and August, and none of the sites had daily temperatures below 20°C in July 2015, likely preventing brook trout from populating the river. The

Sudbury would be classified as a warmwater river, with June-August temperatures >21.7°C, July mean temperatures >22.30°C, and a maximum daily mean temperature >26.30°C (Beauchene et al. 2014), and the fish collected were all cool and warmwater species. Mussels are also sensitive to high water temperatures; according to laboratory tests, *Lampsilis radiata*, one of the two common species in our samples, has a median lethal temperature of 31.0°C and 5% mortality at 25.6°C for 96 hour tests when acclimated to warm (27°C) temperatures (Archambault et al. 2014). Three of the sites (Little Farms, Old Stone Bridge, and Wayland) all had consecutive 4-6 day periods in August 2015 with temperatures >25.6°C, which may be straining or stressing the mussel assemblage. Low flow conditions and associated thermal alteration have also been shown to decrease cold-water insect taxa (Carlisle et al. 2012). Increased temperature can disrupt growth, fecundity, and emergence timing of macroinvertebrates, and ultimately lead to mortality (Vinson 2001). We did not have any thermally-sensitive macroinvertebrate taxa (i.e., class 1 from Poff et al. 2006) at our sites, which may be explained by the warm temperatures. Surface release impoundments (Olden and Naiman 2010), groundwater withdrawals (Poole and Berman 2001), deforestation (Caissie 2006), and urbanization (LeBlanc et al. 1997) all can increase water temperatures, and it is likely that these factors are all influencing water temperatures in the Sudbury.

High concentrations of pollutants, which are often related to low flow conditions (Valenti et al. 2011), may also be impairing biota in the Sudbury. As flows decrease, nutrients and other pollutants discharged into the river from wastewater and surface runoff can become concentrated to the point that algal biomass significantly increases (Taylor et al. 2004, Catford et al. 2007). Thick algal mats were observed covering the substrate during site visits when streamflow was low (Fig. 18), and suggests that nutrient enrichment is a persistent problem, although we did not measure nutrients. Macroinvertebrates are commonly used as

Figure 18 Algal mats observed while surveying during low flow conditions.

indicators of water quality disturbance (Barbour et al. 1999). The proportion of tolerant and moderately tolerant macroinvertebrate taxa within our samples suggests that water quality pollution is a problem in the Sudbury, although the water quality assessment report did not list this reach of the river as impaired in 2001 (O'Brien-Clayton et al. 2005). The fish assemblage also suggests impaired water quality may be an important mechanism of ecosystem alteration. All three pollution intolerant fish species (bridle shiner, brook trout, creek chubsucker) in the TFC were absent from our samples and samples conducted by MDFW on the mainstem Sudbury River dating back to 2001 (Table A9), despite being present in the Concord River basin. The most abundant species (bluegill) is considered tolerant. Similarly, two regional mussel species that appear to be particularly dependent upon clean water (brook floater and creeper) were not sampled. The Sudbury has a known history of pollution problems (McKeon and McLaughlin 1991, Salazar et al. 1996, O'Brien-Clayton et al. 2005). What is unclear is whether these species were lost in the past and never recovered, or if ongoing problems are preventing reestablishment of these populations.

Habitat availability and quality may also be affecting biotic assemblages. Brook trout, common shiner, creek chubsucker, and white sucker all build nests in the gravel substrate for spawning (Raleigh 1982, Curry and Spacie 1984, Hartel et al. 2002). The very low percentage of riffle habitat present in the study area could partially explain the paucity of these species. Gravel runs were virtually absent from the Sudbury, and most runs were dominated by silt (Table 6). Most species we sampled do not share this dependence on riffle habitat for spawning. Species such as chain pickerel, golden shiner, and yellow perch broadcast eggs over the bottom in shallow, still waters (Hartel et al. 2002). Centrarchid species comprised more than half (54.7%) of our sampled individuals, and most centrarchid species sampled, including bluegill, pumpkinseed, and redbreast sunfish, are nest spawners that typically construct nests in shallow, quiet waters (Carlander 1977). Several studies suggest that centrarchid species may persist and become dominant as urbanization and other anthropological disturbances increase (Jones et al. 1999, Waite and Carpenter 2000, Walters et al. 2005, Helms et al. 2009), in part because of their ability to tolerate lentic habitat. The stable, cobble and gravel substrate in riffles is also critical for many riffle-dwelling macroinvertebrates that use rocks for feeding; this explains the high proportion of filter-feeding caddisflies (e.g., Hydropsychidae and Philopotamidae) and black flies (Diptera: Simuliidae) in the riffles. In contrast, the dominance by amphipods (*Gammarus* sp.) and clams (Pisidiidae and Corbiculidae) at the Stone Bridge sites reflects the slower and sandier riffle-run habitat compared to the other two riffle habitats.

Riffle habitat is also critical for providing high-oxygen levels necessary for many fishes and macroinvertebrates. Periods of decreased dissolved oxygen are likely to stress some fish species (Waite and Carpenter 2000, Helms et al. 2005). Fallfish, which require moving water as juveniles (Trial et al. 1983), was the only fluvial-dependent species sampled. In our sampling, almost all fallfish were sampled in the Little Farms Road site, which had the most extensive riffle habitat we surveyed, with nearly one third of the total drop in elevation over 5.3 km occurring in less than a 30 m long section of this site. Macroinvertebrates are also sensitive to oxygen, particularly species in the EPT orders and riffle beetles in the family Elmidae (Elliott 2008). These species could be especially sensitive to periods of no flow with dewatered riffle areas and low oxygen.

Finally, connectivity between habitats in the Sudbury has been hampered by the presence of dams both upstream and downstream of the study site. Anadromous species, such as American shad and Atlantic salmon, may have been present in the system prior to construction of these dams. The loss of such species may have impacts on other species. For example, the unique life cycle of mussels may help to explain the absence of some species. Eastern pearlshell use salmonids (trout and salmon) as a host for the larval stage of development (Nadeau 2008). It is possible that this species was present in the Sudbury at one time, but that the loss of its host species made the system uninhabitable. Similarly, alewife floater appears to be highly dependent upon anadromous fish species, particularly alewife and other alosids (Nadeau 2008). American eel is the only diadromous species that remains in the Sudbury, and this is largely due to this species' ability effectively use fish passage structures and to navigate dry land for short distances.

Future Directions

In this study, we intended to use habitat and flow requirements of the sampled fish and mussel species to quantify the potential effects of flows (and flow alteration) on biota in the Sudbury. Because most of the species found were generalists without specific flow and habitat requirements, there was little potential to identify future effects of flow alteration (as modelled by Zarriello et al. 2010) on species composition. It would be interesting to compare actual flows at the Saxonville gage to reference values for flow metrics as determined from the Sustainable Yield Estimator (SYE, Archfield et al. 2009) to assess the extent of flow alteration; however, the lack of historic biotic data at the same sites limits our ability to define flow-ecology relationships based on past data.

An alternative approach to understanding flow-ecology relationships would be to sample biota across future years with different flow levels to estimate effects of flows on population sizes, particularly for species that may be impacted by flows. To obtain annual flow differences, we could capture natural variability among years or design different flow releases from the upstream dams to explicitly test the effects of alternative flow regimes. Studies would involve quantitative methods to obtain population and age-class estimates for each taxonomic group, which are essential for capturing population-level variation. Such studies could also include habitat-specific sampling to make direct linkages between habitat availability at different flow levels to abundances of species. For fishes, sampling could include blocking specific habitat units and do multi-pass fish depletion, using pre-positioned electrofishing device (e.g., Bain et al. 1988), or conducting "kick sets" at random locations within habitat types. For mussels, quantitative, habitat-specific sampling is typically conducted by randomly placing quadrats within habitat types, or, where mussels are scarce, by conducting visual surveys and collecting additional habitat-specific data (e.g., water depth, substrate, temperature) at the locations of mussels. For macroinvertebrates, quantitative sampling devices (e.g., Surber sampler, stove-pipe corer, multi-plate sampler) could be used in multiple habitats to obtain density estimates in various habitats. Importantly, this habitat-specific biotic sampling would need to be conducted within the same season each year and combined with measures of habitat availability and quality at different flow levels to assess the effect of flow on habitat use by aquatic biota. Ultimately, these data could be used to predict losses of taxa or changes in densities at different flow levels.

One limitation of this study is that we only sampled a single river, so there was no opportunity to compare biota across sites with different levels of hydrologic alteration. Although the TFC approach allowed us to consider taxa that were expected in the Sudbury River given undisturbed conditions, data was not available to develop expected assemblages for mussels and macroinvertebrates. Moreover, this approach cannot parse causes of altered assemblages. Comparison of Sudbury River data to other, similar rivers with a wide range in flows and flow alteration (particularly groundwater withdrawals, e.g., following Weiskel et al. 2010) would help to determine if poor assemblage quality may be due to flow alteration. Armstrong et al. (2011) examined fish assemblages in Massachusetts and found that fluvial fish species richness and abundance were affected by percent alteration of the August median flow due to groundwater withdrawals, suggesting that flow alteration is an important driver of fish assemblages. However, this study estimated groundwater withdrawals and simulated unaltered flows, and did not encompass flow alteration from land use or impervious cover, surface water withdrawals, or other active flow management that are known sources of hydrologic impairment in the Sudbury. Other studies have investigated fish (e.g., Poff and Zimmerman 2010) and macroinvertebrate (e.g., Kennen et al. 2010, Carlisle et al. 2012) assemblages in relation to measured flows at sites with USGS gages, and a similar approach that focused on rivers of comparable size, slope, and geology to the Sudbury River would be a useful next step. A comparative approach across sites would also be useful to assess the extent to which altered water quality may be impacting biotic assemblages; water quality data in the Sudbury River is available through OARS (www.oars3rivers.org) from 1992 to present and would be valuable to analyze to better understand the relative importance of water quality and water quantity impacts.

We selected a subset of reaches within the targeted 5-km section of the Sudbury River for sampling, based primarily on accessibility and presence of mussels (based on observations while canoeing the entire section), with the goal of spacing reaches throughout the river section. We did not collect information on habitat availability (e.g., area of pool, riffle, and run habitats) and quality (e.g., depth, bed texture, wood) throughout the 5-km section outside of our study reaches, and such data is important to understand the extent to which our sampled reaches are representative, and allow us to extrapolate results to the larger section. A longitudinal survey could also identify unique habitats for future sampling. For example, there is an oxbow located adjacent to the Little Farms Road site that provides shallow, sandy habitat that may harbor unique taxa and be more affected by low flow conditions than the main stem of the Sudbury.

Conclusion

Here, we provided data on fish, mussel, and macroinvertebrate species inhabiting a 5-km section of the Sudbury River designated as a Wild and Scenic River. Despite this designation, the biotic assemblage indicates a stressed system likely due to a combination of watershed-scale impacts, including hydrologic alteration. The Sudbury River has a long history of hydrological alteration related to impoundments, withdrawals, and urbanization, resulting in a species assemblage that would be expected in a river with an altered hydrological regime. Given the current trends of decreasing low discharge volumes, yhr decreased magnitude of low flows predicted by climate change (Demaria et al. 2016), and anticipated future human impacts, there is potential that shallow riffle habitat may go dry. Under such conditions, remaining fluvial fish species such as fallfish, as well as riffle-inhabiting mussels and macroinvertebrates could potentially be impacted. Additionally, decreased water quality and increased temperatures during such periods could potentially impact a variety of biota. While this study indicates that biota are likely impacted by a variety of stressors, additional surveys are needed to understand mechanisms by which these stressors impact biota and predict potential changes with increased hydrologic alteration.

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Appendix

Table A1 Densities (no. m^{-2}) of macroinvertebrates collected from riffle and riffle-run habitats at three sites on 12 August 2014.

Phylum: Class: Order	**Family**	**Taxon**	**PTV[a]**	**Danforth**	**Little Farms**	**Stone Bridge**	**Total**	**%**
Arthropoda: Insecta								
Coleoptera	Elmidae	*Dubiraphia sp.*	6.9	0.0	0.0	5.3	5.3	0.0
		Macronychus glabratus	5.7	8.5	0.0	0.0	8.5	0.1
		Microcylloepus pusillus	3.7	0.0	0.0	5.3	5.3	0.0
		Stenelmis sp.	5.7	8.5	0.0	0.0	8.5	0.1
Diptera	Ceratopogonidae	*Bezzia sp.*	6.3	0.0	0.0	5.3	5.3	0.0
	Chironomidae	*Ablabesmyia sp.*	5.3	0.0	0.0	5.3	5.3	0.0
		Cardiocladius obscurus	5.6	0.0	66.7	5.3	72.0	0.6
		Chironomini	8.3	0.0	0.0	5.3	5.3	0.0
		Cladotanytarsus sp.	5.5	0.0	0.0	5.3	5.3	0.0
		Cricotopus bicinctus	7	0.0	44.4	15.9	60.3	0.5
		Cricotopus sp.	6.3	0.0	200.0	0.0	200.0	1.8
		Cricotopus/Orthocladius sp.	5.5	25.6	44.4	15.9	86.0	0.8
		Diplocladius cultriger	3.7	8.5	0.0	10.6	19.1	0.2
		Orthocladiinae	4.7	25.6	22.2	0.0	47.9	0.4
		Polypedilum aviceps	5.3	8.5	0.0	0.0	8.5	0.1
		Polypedilum flavum	5.3	51.3	133.3	5.3	189.9	1.7
		Potthastia longimana gr.	4.7	8.5	22.2	0.0	30.8	0.3
		Rheocricotopus sp.	5.2	0.0	22.2	0.0	22.2	0.2
		Rheotanytarsus exiguus gr.	4.5	59.8	244.4	15.9	320.1	2.8
		Rheotanytarsus pellucidus	4	42.7	22.2	10.6	75.5	0.7
		Rheotanytarsus sp.	4	17.1	22.2	0.0	39.3	0.3
		Tanypodinae	6	8.5	0.0	0.0	8.5	0.1
		Tanytarsus sp.	6	8.5	0.0	0.0	8.5	0.1
		Tvetenia sp.	5.75	8.5	0.0	0.0	8.5	0.1
		Tvetenia vitracies	5.75	76.9	288.9	0.0	365.8	3.2
	Simuliidae	*Simulium sp.*	5.6	25.6	222.2	5.3	253.2	2.2
	Tipulidae	*Antocha sp.*	3.7	0.0	22.2	15.9	38.1	0.3
Ephemeroptera	Baetidae	*Baetis flavistriga*	2.7	8.5	22.2	10.6	41.4	0.4
		Baetis intercalaris	2.7	0.0	111.1	0.0	111.1	1.0
		Iswaeon anoka	2.7	0.0	155.6	5.3	160.8	1.4
Trichoptera	Hydropsychidae	*Cheumatopsyche sp.*	5.5	641.0	800.0	52.9	1493.9	13.3
		Hydropsyche betteni	5.7	282.1	1733.3	68.8	2084.2	18.5
		Hydropsyche sp.	4.5	0.0	44.4	0.0	44.4	0.4
		Hydropsyche sparna	4.5	8.5	0.0	5.3	13.8	0.1
	Hydroptilidae	*Hydroptila sp.*	4.7	0.0	0.0	21.2	21.2	0.2
	Leptoceridae	*Ceraclea sp.*	4	59.8	0.0	5.3	65.1	0.6
		Oecetis sp.	4.3	25.6	111.1	10.6	147.3	1.3
	Philopotamidae	*Chimarra obscura*	4	359.0	2111.1	15.9	2486.0	22.1
		Philopotamidae	4	68.4	155.6	5.3	229.2	2.0
Arthropoda: Arachnida								
Acariformes	Hygrobatidae	*Hygrobates sp.*	6	8.5	0.0	15.9	24.4	0.2
	Lebertiidae	*Lebertia sp.*	6	0.0	0.0	79.4	79.4	0.7
	Sperchonidae	*Sperchon sp.*	6	85.5	133.3	15.9	234.7	2.1
Arthropoda: Crustacea							0.0	0.0
Amphipoda	Gammaridae	*Gammarus sp.*	5.3	478.6	111.1	650.8	1240.5	11.0
Ostracoda		Ostracoda	nd	0.0	0.0	10.6	10.6	0.1
Annelida: Oligochaeta								
Lumbriculida	Lumbriculidae	Lumbriculidae	7.7	0.0	0.0	5.3	5.3	0.0
Tubificida	Enchytraeidae	Enchytraeidae	7	0.0	0.0	5.3	5.3	0.0
	Naididae	Naidinae	8	0.0	0.0	5.3	5.3	0.0
		Tubificinae w/out capilliform setae	8	0.0	0.0	10.6	10.6	0.1

[a]Pollution tolerant values based on Klemm et al. (2002). nd = no data on pollution tolerance; taxon removed from calculations.

Table A1. Continued

Phylum: Class: Order	Family	Taxon	PTV[a]	Danforth	Little Farms	Stone Bridge	Total	%
Mollusca: Gastropoda								
Basommatophora	Physidae	Physidae	7.3	0.0	0.0	127.0	127.0	1.1
	Planorbidae	*Menetus dilatatus*	4.7	17.1	0.0	10.6	27.7	0.2
Mesogastropoda	Hydrobiidae	*Amnicola sp.*	nd	170.9	22.2	79.4	272.5	2.4
Mollusca: Pelecypoda								
Veneroida	Corbiculidae	*Corbicula fluminea*	6.3	0.0	22.2	52.9	75.1	0.7
	Pisidiidae	*Musculium sp.*	7.5	0.0	0.0	26.5	26.5	0.2
		Pisidiidae	8	34.2	22.2	190.5	246.9	2.2
		Pisidium sp.	8	0.0	0.0	31.7	31.7	0.3
Nemata		Nemata	6	8.5	22.2	0.0	30.8	0.3

[a]Pollution tolerant values based on Klemm et al. (2002). nd = no data on pollution tolerance; taxon removed from calculations.

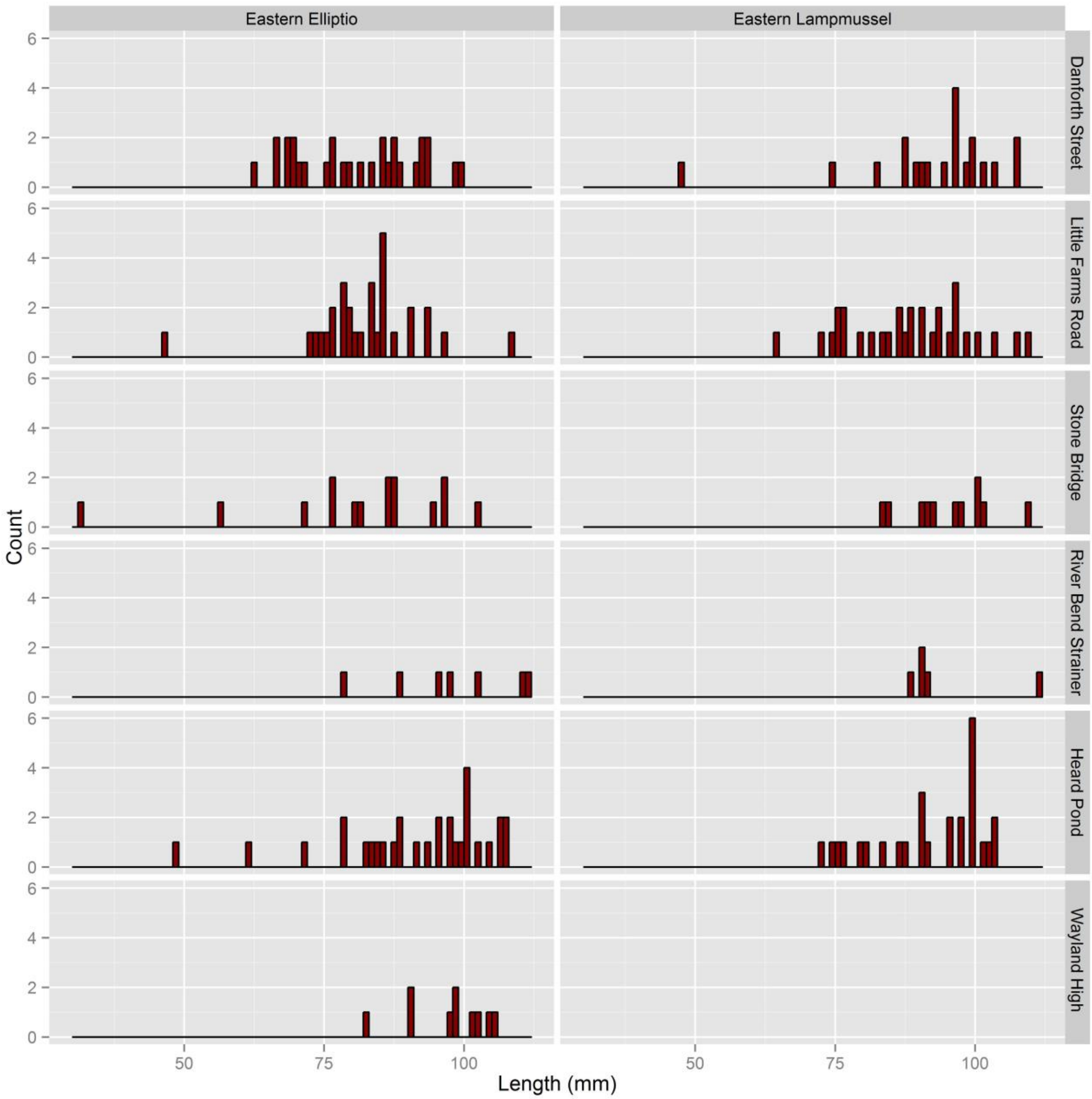

Figure A1 Histograms of mussel size distribution for the two most abundant mussel species, Eastern Elliptio and Eastern Lampmussel, at each of the six mussel sampling sites. Sites are ordered upstream to downstream from the top.

Table A2 Mussel species at each site with the numbers of male (M), female (F), unknown (U), and condition (I-V) for those that were evaluated for these characteristics. 'Jv' refers to a juvenile individual whose sex could not be determined.

Site Species	Total	Sex			Condition				
		M	F	U	I	II	III	IV	V
Danforth Street									
Eastern elliptio	263								
Eastern lampmussel	206	104	33	1	5	5	4	2	4
Eastern pondmussel	3		3					3	
Eastern floater	1								
Triangle floater	2								2
Little Farms Road									
Eastern elliptio	34				11	7	7	3	2
Eastern lampmussel	42	20	10		5	6	2	4	13
Eastern pondmussel	3	2		Jv	2		1		
Eastern floater	0								
Triangle floater	0								
Stone Bridge									
Eastern elliptio	31				6	5	4		
Eastern lampmussel	11	9	1		1	4	2	1	3
Eastern pondmussel	0								
Eastern floater	0								
Triangle floater	0								
River Bend Strainer									
Eastern elliptio	9				2	1	1	1	2
Eastern lampmussel	5	4	1			2			3
Eastern pondmussel									
Eastern floater	1								
Triangle floater									
Heard Pond Meander									
Eastern elliptio	77				5	7	6	4	8
Eastern lampmussel	27	14	10	3	4	5	4	9	5
Eastern pondmussel	0								
Eastern floater	0								
Triangle floater	1								1
Wayland High School									
Eastern elliptio	10				3	3		3	1
Eastern lampmussel	0								
Eastern pondmussel	0								
Eastern floater	1				1				
Triangle floater	0								

Table A3 Selected biotic traits for sampled mussel species. Based on Bogan (2002), Natureserve (2014), Bogan and Alderman (2008), Nadeau (2008) and Galbraith et al. (2012).

	Life-Stage	Timing		Habitat			Hydro-Ecology Relationships			Hosts	
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit		Comments
Eastern elliptio (*Elliptio complanata*)	Spawning	April-mid June	>20°C	All types		May tolerate periods of extreme hypoxia (1 mg/L), though juveniles less tolerant	Tolerate wide range of current		Ponds, lakes, rivers	Wide range of host species	This is a species complex that may constitute a large number of species
	Brooding	Spring-late summer	Temperature								
	Glochidia Release	1 month after spawning	Temperature								
Eastern pondmussel (*Ligumia nasuta*)	Spawning	Late Summer		No distinct preference			Tolerate wide range of current		Coastal ponds to rivers with strong currents	Not yet determined, possible coastal species	Species of special concern in Massachusetts
	Brooding										
	Glochidia Release	Spring after fertilization									
Eastern lampmussel (*Lampsilis radiata*)	Spawning	Mid to late summer		Prefers sand or gravel, but will use wide range			None to significant		Streams, rivers, ponds, and lakes	Includes rockbass, pumpkinseed, bluegill, largemouth bass, yellow perch, black crappie	
	Brooding										
	Glochidia Release	Spring after fertilization									
Eastern floater (*Pyganodon cataracta*)	Spawning	August		Wide variety, particularly tolerant of deep silt and mud			Slow moving or standing waters		Wide range	Common carp, bluegill, pumpkinseed, yellow perch, white sucker, rock bass, three-spine stickleback	
	Brooding										
	Glochidia Release	Spring after fertilization									
Triangle floater (*Alasmidonta undulata*)	Spawning	Summer		Seems to prefer sand and gravel, but found in wide range			Mainly quiet waters with some current, avoids riffles		Streams, rivers, and lakes	Wide range, diverse hosts	Restricted to sites with stable banks
	Brooding										
	Glochidia Release	Spring after fertilization									

Table A4 Selected biotic traits for Massachusetts mussel species that were not sampled. Information from Swartz and Nadeau (2007), Nadeau and Victoria (2003), Nadeau (2008).

	Life-Stage	**Timing**		**Habitat**			**Hydro-Ecology Relationships**			**Hosts**	
		Months	Cue	Substrate	Temp	DO	Velocity	Depth	Hydraulic Habitat Unit		Comments
Eastern pearlshell (*Margaritifera margaritifera*)	Spawning			Firm sand, gravel, or cobble	Cool	High			Streams and small rivers that support trout. Tolerates fast, high-gradient streams. Never in lakes, ponds, or warmwater streams.	Salmonids	Thought intolerant of eutrophication resulting from urbanization and agriculture. May live 200 years.
	Brooding										
	Glochidia Release	October. Overwinter on hosts.									
Brook floater (*Alasmidonta varicosa*)	Spawning	Fertilization in summer		Course sand and gravel			Swift		Free-flowing rivers and streams, clean water. Not high-gradient. Never lakes or reservoirs.	Longnose dace, blacknose dace, golden shiners, pumpkinseed, slimy sculpin, yellow perch	
	Brooding										
	Glochidia Release	April – June year after fertilization									
Dwarf wedgemussel (*Alasmidonta heterodon*)	Spawning	Late summer		Stable. Clay, sand, gravel, pebble.			Moderate		Streams and rivers.	Tessellated darter, slimy sculpin, mottled sculpin, Atlantic salmon, striped bass	Federally endangered
	Brooding										
	Glochidia Release	March and May following fertilization									
Creeper (*Strophitus undulatus*)	Spawning	Fertilization in summer		Sand and fine gravel			Low to moderate		Clean flowing water, though found in lakes in some places.	Wide range, including largemouth bass, creek chub, fallfish, fathead minnow, bluegill.	
	Brooding										
	Glochidia Release	Spring following fertilization									

Yellow lampmussel (*Lampsilis cariosa*)	Spawning	Fertilization in late summer[1]	Variety; silt, sand, gravel, and cobble. Sand and fine gravel preferred.		Prefers medium to large rivers, though may be found in lakes and ponds.	White perch, yellow perch, largemouth bass and, potentially, banded killifish, chain pickerel, white sucker, and smallmouth bass.	
	Brooding						
	Glochidia Release	Spring following fertilization					
Alewife floater (*Anodonta implicata*)	Spawning	Fertilized in August	Variety; silt, sand, and gravel		Streams, rivers, and lakes accessible by hosts	Alwife confirmed, although white sucker, threespine stickleback, white perch, and pumpkinseed suspected	Although other fish hosts suspected, range appears limited by alewife distribution.
	Brooding						
	Glochidia Release	Spring following fertilization					
Tidewater mucket (*Leptodea ochracea*)	Spawning	Late summer	Variety; silt, sand, gravel, cobble	Mainly quiet waters with some current, avoids riffles	Coastal lakes, ponds, and slow moving rivers	White perch, also banded killifish and alewife are potential hosts	Restricted to sites with stable banks
	Brooding						
	Glochidia Release	Spring after fertilization					

Table A5 Abundance of fish species sampled at five locations, including the mean length and the standard deviation (SD) of the length at each site.

Location		Danforth Street	Little Farms Road	Heard Pond Meander	Wayland High School	Pelham Island Road
American eel *Anguilla rostrata*	Count	6	50	5	5	2
	Mean Length (mm)	193.3	243.3	484	351.0	497.5
	SD Length	68.6	101.1	117.7	174.9	NA
Black crappie *Pomoxis nigromaculatus*	Count	1			6	2
	Mean Length (mm)	149.0			193.5	202.5
	SD Length	NA			71.4	NA
Bluegill *Lepomis machrochirus*	Count	151	84	27	42	46
	Mean Length (mm)	149.7	146.3	143.4	130.2	141.4
	SD Length	25.1	31.2	34.4	26.5	30.3
Brown Bullhead *Ameiurus nebulosis*	Count					1
	Mean Length (mm)					289
	SD Length					NA
Chain pickerel *Esox niger*	Count		2	1	1	1
	Mean Length (mm)		108	125.0	120.0	93
	SD Length		NA	NA	NA	NA
Common carp *Cyprinus carpio*	Count				1	5
	Mean Length (mm)				806	602.2
	SD Length				NA	129.4
Fallfish *Semotilus corporalis*	Count	1	21			
	Mean Length (mm)	66	63.4			
	SD Length	NA	29.7			
Golden shiner *Notemigonus crysoleucas*	Count		1	2	7	26
	Mean Length (mm)		107.0	157.0	155.9	137.8
	SD Length		NA	NA	13.9	11.3
Largemouth bass *Micropterus salmoides*	Count	10	17	8	9	2
	Mean Length (mm)	130.8	131.2	334.0	373.0	380.5
	SD Length	143.8	114.3	124.1	67.9	NA
Pumpkinseed *Lepomis gibbosus*	Count	2		6	12	4
	Mean Length (mm)	164.5		150.2	131	100.5
	SD Length	NA		24.8	23.9	19.1
Redbreast sunfish *Lepomis auritus*	Count	6	5	1		
	Mean Length (mm)	85.0	107.0	120.0		
	SD Length	27.8	22.1	NA		
Redfin pickerel *Esox americanus americanus*	Count					2
	Mean Length (mm)					168
	SD Length					NA
Rock bass *Ambloplites rupestris*	Count	1				
	Mean Length (mm)	217.0				
	SD Length	NA				

Location		Danforth Street	Little Farms Road	Heard Pond Meander	Wayland High School	Pelham Island Road
Spottail shiner *Notropis hudsonius*	Count			5	9	
	Mean Length (mm)			104.0	94.2	
	SD Length			3.7	26.0	
White sucker *Catostomus commersonii*	Count	10	2	23	17	2
	Mean Length (mm)	412.8	69.5	462.1	453.1	477.5
	SD Length	63.7	NA	43.0	37.5	NA
Yellow bullhead *Ameiurus natalis*	Count	1	3	3	1	1
	Mean Length (mm)	38.0	154.0	240.0	240.0	277.0
	SD Length	NA	95.6	5.6	NA	NA
Yellow perch *Perca flavescens*	Count	6		20	88	33
	Mean Length (mm)	182.0		123.9	109.4	152.6
	SD Length	30.1		52.1	44.2	50.8
Total Abundance		**195**	**185**	**101**	**198**	**137**

Table A6 Selected biotic traits for sampled fish species. Information from Warren and Burr (2014), Lee et al. (1980), Carlander (1977), Hartel et al. (2002), Scott and Crossman (1973), Doherty et al. (2010), and Trial et al. (1983).

	Life-Stage	Life Cycle		Habitat		Geographic Range (Native)	Hydro-Ecology Relationships			Habitat Class	
		Location/Habitat	Season	Substrate	Temp		Velocity	Depth	Hydraulic Habitat Unit		Comments
American eel (*Anguilla rostrata*)	Spawning	Sargasso Sea – Open Ocean	February and March	All types		Atlantic coastal drainages from Greenland to central America	Tolerate wide range of current		Ponds, lakes, large rivers, small streams	MG	Catadromous species that spawns in the ocean and uses freshwater for most of its life history
	Juvenile	Estuarine w/movements into freshwater									
	Adult	Freshwater									
Black crappie (*Pomoxis nigromaculatus*)	Spawning	Gravel or sand in 0.25 to 6.1 m of water C at the base of vegetation	March to July – temperature dependant	Sandy to muddy with abundant aquatic vegetation	Warm	Southern Manitoba to Quebec, south to Florida and Texas. Not native to Massachusetts	Quiet waters		Large ponds and lakes. Slow moving portions of rivers	MG	Reconstruction of native range difficult due to wide transplantation
	Juvenile										
	Adult										
Bluegill (*Lepomis machrochirus*)	Spawning	Shallow water up to 3.3 m, but < 1 m more common over variety of substrate, gravel preferred	May spawn throughout growing season		Preferred temps range from 28°C to 33°C	Coastal Virginia to Florida, west to Texas, and north from western Minnesota to western New York.	Still to slow moving	Shallow depths	Lakes, ponds, rivers, and creeks	MG	Not native to Massachusetts
	Juvenile										
	Adult										
Brown bullhead (*Ameiurus nebulosus*)	Spawning		Late May through June	Sandy to muddy	Can survive temps up to 36°C and are dormant in winter	Throughout eastern half of US and into southern Canada	Backwaters		Lakes, ponds, and backwaters of streams and rivers	MG	Only catfish native to Massachusetts
	Juvenile										
	Adult										
Chain pickerel (*Esox niger*)	Spawning	No nest, eggs scattered over vegetation or detritus	Late winter to spring, 8.3°C to 11.1°C			Atlantic coastal plain Florida to southwest Maine	Quiet, backwaters in rivers		Lakes, ponds, and medium to large rivers	MG	Remains found in a Sudbury River archaeological site
	Juvenile										
	Adult										

	Life-Stage	Life Cycle		Habitat		Geographic Range (Native)	Hydro-Ecology Relationships			Habitat Class	
		Location/Habitat	Season	Substrate	Temp		Velocity	Depth	Hydraulic Habitat Unit		Comments
Common carp (*Cyprinus carpio*)	Spawning	Inshore areas with aquatic or seasonally flooded vegetation. Broadcast spawners	Late spring into late summer, > 15°C			Eurasia	Still to slow moving		Lakes, ponds, large rivers	MG	Introduced in North America. May alter habitat in ways that cause declines in native fish assemblages
	Juvenile										
	Adult	Winter in deep water, but move inshore during spring									
Fallfish (*Semotilus corporalis*)	Spawning	Males build nests in areas of rock and gravel by moving pebbles with mouth. Depths < 0.5 m in quiet waters with overhead cover	Mid-April, > 15°C	Rock and gravel	Mostly found in water < 28°C	Ontario south to Virginia	Faster waters in younger individuals, pools and runs associated with cascades in adults		Commonly middle reaches of streams, some ponds and reservoirs	FS	Though currently uncommon in E. Mass, historic records suggest past abundance
	Juvenile	Frequent rapid water more than adults									
	Adult	Pools and deep runs, commonly located near cascades									
Golden shiner (*Notemigonus crysoleucas*)	Spawning	Broadcast spawners, over submerged vegetation in shallow water	May - August			Maritime provinces south to Florida, west to Texas	Sluggish, quiet water		Ponds, lakes, streams, rivers	MG	
	Juvenile										
	Adult	Access to extensive shallows									
Largemouth bass (*Micropterus salmoides*)	Spawning	Nests on sand, gravel, roots, or aquatic vegetation, often near boulders or pilings. Will not use silt.	Thermal cues, anywhere from mid-January into July. May-June in New England.		Prefer summer water temps ranging from 26°C to 32°C, depending on range.	East of Rocky Mountains from southern Quebec south through Mississippi River to Gulf of Mexico	Nonflowing with aquatic vegetation		Lakes, ponds, slow moving rivers	MG	Widely introduced gamefish, not native to New England
	Juvenile										
	Adult										

	Life-Stage	Life Cycle		Habitat		Geographic Range (Native)	Hydro-Ecology Relationships			Habitat Class	
		Location/Habitat	Season	Substrate	Temp		Velocity	Depth	Hydraulic Habitat Unit		Comments
Pumpkinseed (*Lepomis gibbosus*)	Spawning	Over constructed depressions in shallows over sand or gravel	Late spring through mid-summer	Rocky or plant covered	Selected temps from 31°C-31.7°C in lab study	Southern Canada, Upper Mississippi to Atlantic coast south to Georgia	Quiet, vegetation filled waters		Lakes, ponds, marshes, slow moving streams	MG	
	Juvenile	Shallower than adult									
	Adult	Vegetated waters									
Redbreast sunfish (*Lepomis auritus*)	Spawning	Construct nest near objects such as rocks and woody debris	Late spring through mid-summer	Rocky	Wide range	Atlantic coastal drainages from Maine to Florida, and along Gulf to Texas	Quiet, non-vegetated		Ponds, lakes, slow moving streams and rivers	MG	Appears to have been more common in Mass. historically
	Juvenile										
	Adult										
Redfin pickerel (*Esox americanus americanus*)	Spawning	No nest, heavily vegetated margins of streams and ponds	Spring, but fall also reported. Likely cued by temperature			Atlantic coastal plain from southern New Hampshire south to Florida	Still, quiet		Streams, drainage canals and less often, ponds and bays of small lakes	MG	Hybridizes with chain pickerel. Eastern subspecies of *Esox americanus*, which has western subspecies *E. a. vermiculatus*
	Juvenile										
	Adult		Heavily vegetated								
Rock bass (*Ambloplites rupestris*)	Spawning	Nests in shallow water in areas of silt-free gravel and rocky bottoms	Initiated at 20.5°C-21°C. April-June in New York	Rocky, never silt	Prefers cool waters	Southern Massachusetts to southern Ontario. Western tribs of upper Mississippi River south to Alabama			Littoral regions of larger lakes, small lakes, streams	MG	Hartel et al. report that Rock Bass were first introduced in Massachusetts in 1934
	Juvenile										
	Adult	Bottom dwelling. Extensive cover such as submerged stumps or large rocks									
Spottail shiner (*Notropis hudsonius*)	Spawning	Shallow, sandy shoals	Spring-early summer			Georgia to New England, west through Great Lakes, extending to Mackenzie River in Canada	Wide range		Lakes, large, sluggish rivers to small montane streams	MG	
	Juvenile										
	Adult										

	Life-Stage	Life Cycle		Habitat		Geographic Range (Native)	Hydro-Ecology Relationships			Habitat Class	
		Location/Habitat	Season	Substrate	Temp		Velocity	Depth	Hydraulic Habitat Unit		Comments
White sucker (*Catostomus commersonii*)	Spawning	Migrate several km to fast flowing gravel runs of tributaries, or shoal areas if tributaries not available	Mid-April to May, lasting only three weeks	Depositional areas of fine substrates		Arctic circle south to New Mexico and Georgia except Pacific slope drainages	Slow to moderate currents and pools		Ponds, lakes, and rivers	FD	Long range spawning movements suggest juveniles migrate long distance to identify adult home range
	Juvenile										
	Adult	Slow to moderate currents. Some studies show strong home range site fidelity									
Yellow bullhead (*Ameiurus natalis*)	Spawning		Mid-May to early June	Soft bottom		Most of eastern and central US and adjacent southern Canada.			Low gradient streams, shallow bays of ponds and lakes	MG	Introduced in Massachusetts
	Juvenile										
	Adult										
Yellow perch (*Perca flavescens*)	Spawning	Eggs deposited over logs and vegetation	Early April and May	Rock ledges or submerged bars in deeper water		E. Coast from Nova Scotia to South Carolina, northwest to Montana and north to Great Slave Lake.	Still, slow moving		Lakes, ponds, larger streams and rivers	MG	
	Juvenile	Weedy shallows									
	Adult										

Table A7 Selected biotic traits for fish species present in the TFC that were not sampled in this study. Based on Lee et al. 1980, Wismer and Christie (1987), Hartel et al. (2002), and Natureserve (2014).

	Life-Stage	Life Cycle		Habitat		Geographic Range (Native)	Hydro-Ecology Relationships			Habitat Class	
		Location/Habitat	Season	Substrate	Temp		Velocity	Depth	Hydraulic Habitat Unit		Comments
Bridle shiner (*Notropis bifrenatus*)	Spawning	Spawn near surface and eggs fall to bottom	May to mid-July	Well vegetated		Southern New England to South Carolina	Quiet water		Ponds, rivers, brooks	MG	Hartel et al. (2002) noted observations from all major Mass basins, but that these are declining. Species of special concern in MA
	Juvenile										
	Adult										
Brook trout (*Salvelinus fontinalis*)	Spawning	Gravel riffles	Late September through November		Cool, do not tolerate extended periods higher than 20°C. Upper incipient lethal ~25°C.	E. Canada from Hudson Bay drainages, E. US west to Minnesota, south in Appalachians to Georgia	Flowing		High gradient mountain streams to low gradient meander brooks	FS	Pond populations occur, but are rare in MA E. Mass populations have declined. Require clean, cold water
	Juvenile										
	Adult										
Common shiner (*Luxilus cornutus*)	Spawning	Gravel beds in riffles 13-44 mm deep, undertakes migrations. Substrate 5-60 mm.	May	Gravel to rubble	Cool, upper incipient lethal temperature ~31°C	Upper half of Atlantic slope, Great Lakes drainages, southern extreme of Hudson Bay drainages.	Moderate to swift		Large rivers to small streams	FD	Require relatively clean water and does not tolerate pH below 5.8. Hartel notes this species is most common in W. Mass but may have been more common in east in past. Historic records from Charles River basin; currently in some tribs. to Merrimack
	Juvenile										
	Adult	Pools below cascades, not in deadwater or long pools									
Creek chubsucker (*Erimyzon oblongus*)	Spawning	Nests over gravel runs	Early spring	Sand and gravel bottomed pools		Atlantic slope from S. Maine to Georgia.	Pools, but utlize runs for spawning		Headwaters, creeks, and small rivers. Seldom if ever occupies impoundments	FS	Sensitive to pollutants, particularly silt. Kashiwagi and Richards (2009) reported sampling nine individuals from one location in the Assabet River in 1999.
	Juvenile	Headwater rivulets or marshes									
	Adult										

	Life-Stage	Life Cycle		Habitat		Geographic Range (Native)	Hydro-Ecology Relationships			Habitat Class	
		Location/Habitat	Season	Substrate	Temp		Velocity	Depth	Hydraulic Habitat Unit		Comments
Tesselated darter (*Etheostoma olmstedi*)	Spawning	Male makes nest on underside of log or rock, where eggs are deposited	Early spring	Rubble, sand, or mud		E. coast from Quebec to Georgia. Hartel shows absent from Boston area in Massachusetts	Moving water		Seldom found in lakes or ponds	FS	
	Juvenile										
	Adult										

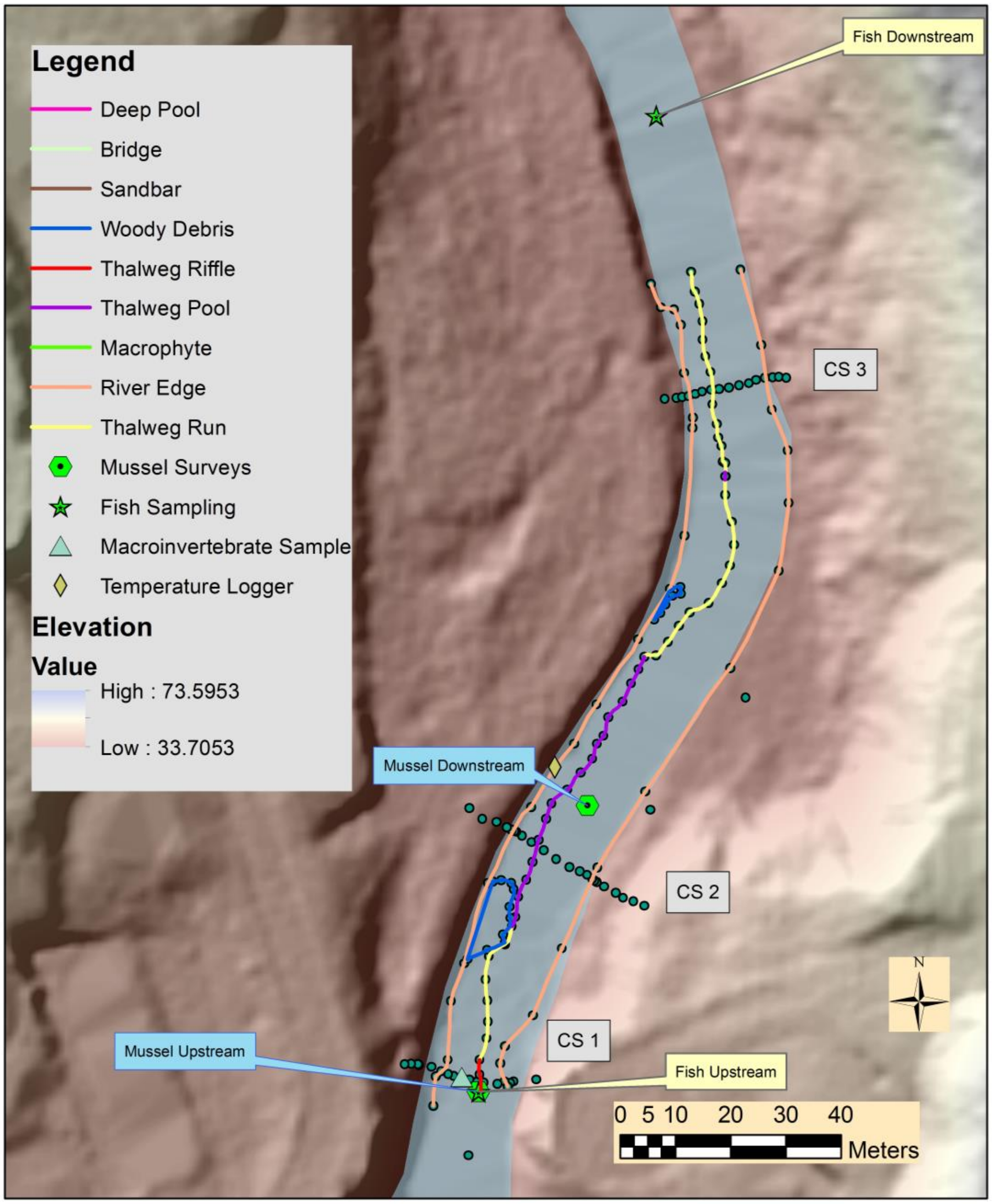

Figure A2 Survey data for Danforth Street site. CS = cross section.

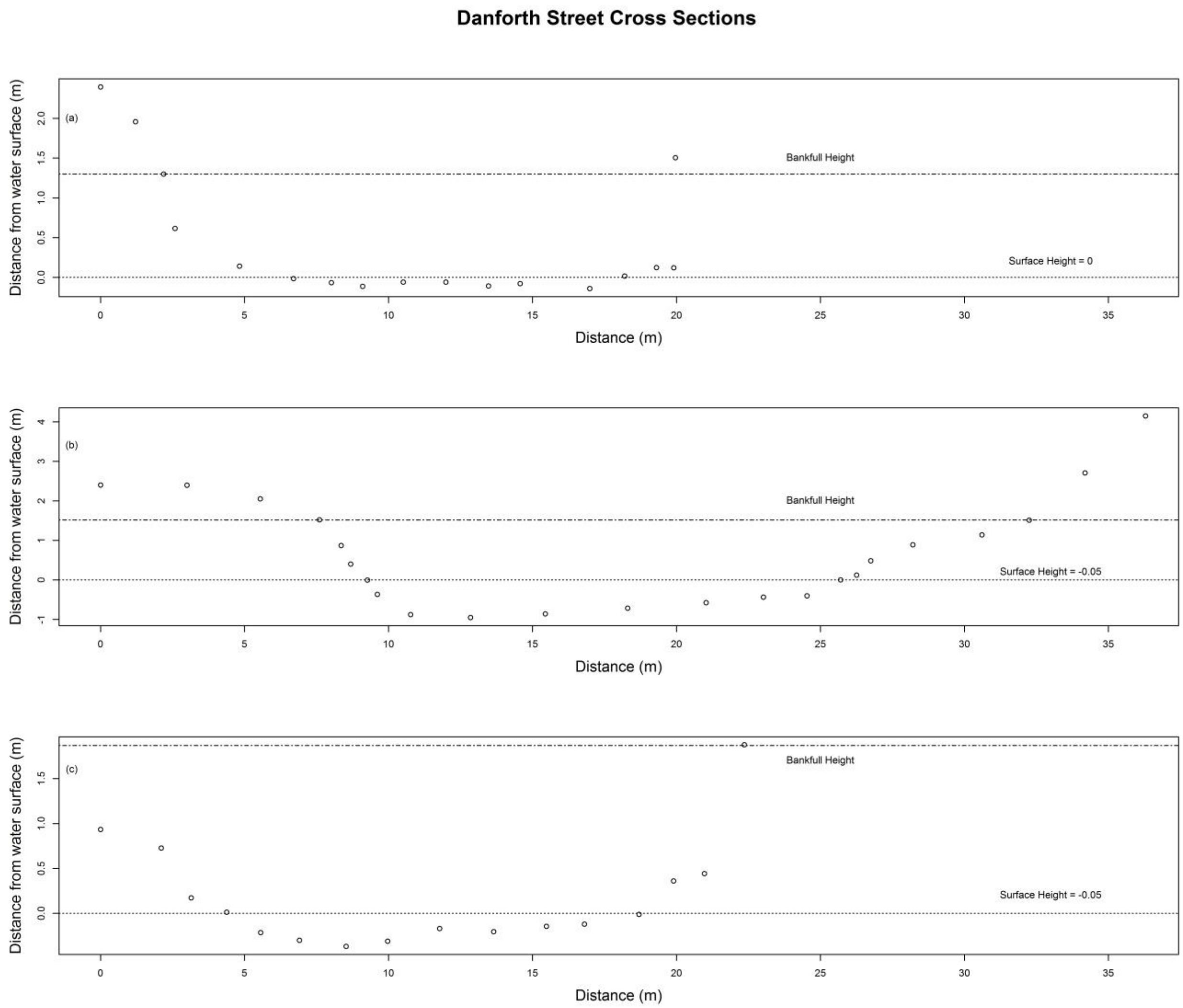

Figure A3 Profiles of a) cross section 1, riffle habitat b) cross section 2, pool habitat c) cross section 3, run habitat at Danforth Street site. Cross sections are ordered 1-3 from upstream to downstream. Left side represents river left and right side represents river right. Surface height represents approximate height (m) at water surface relative to the top of the reach.

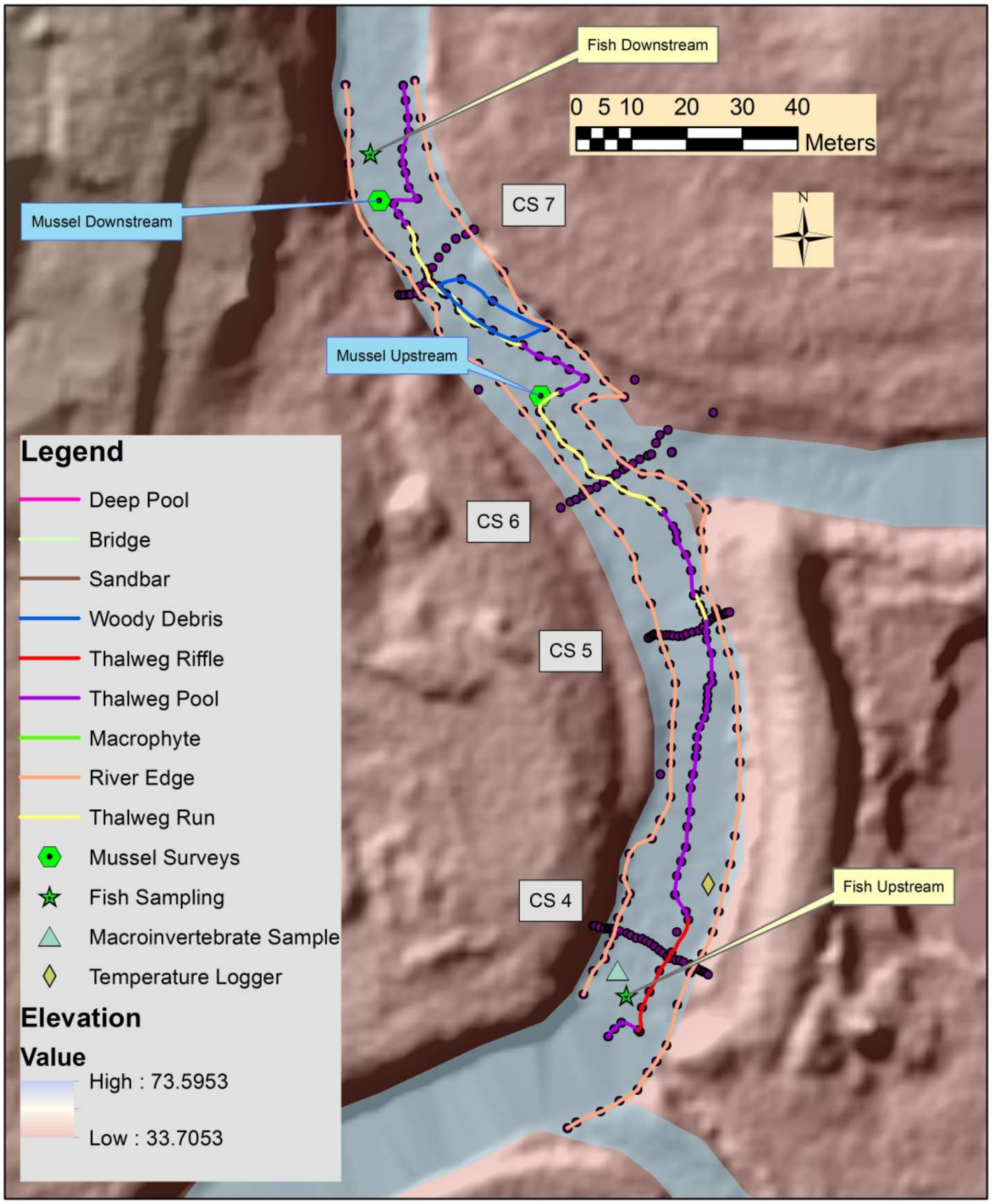

Figure A4 Survey data for Little Farms Road site. CS = cross section.

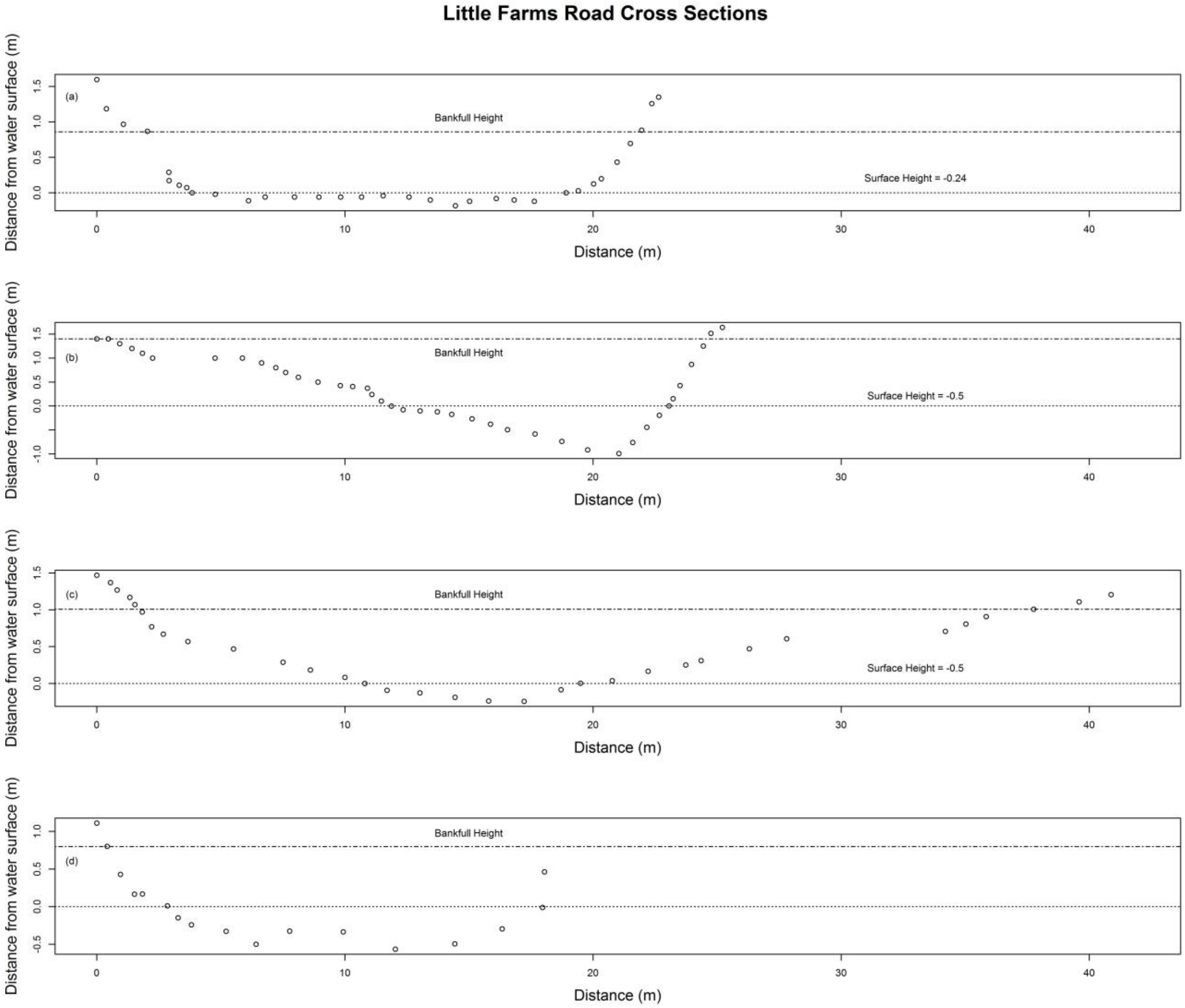

Figure A5 Profiles of a) cross section 4, riffle habitat b) cross section 5, pool habitat c) cross section 6, run habitat d) cross section 7, slow run habitat at Little Farms Road site. Cross sections are ordered 4-7 from upstream to downstream. Left side represents river left and right side represents river right. Surface height represents approximate height (m) at water surface relative to the top of the reach, where available.

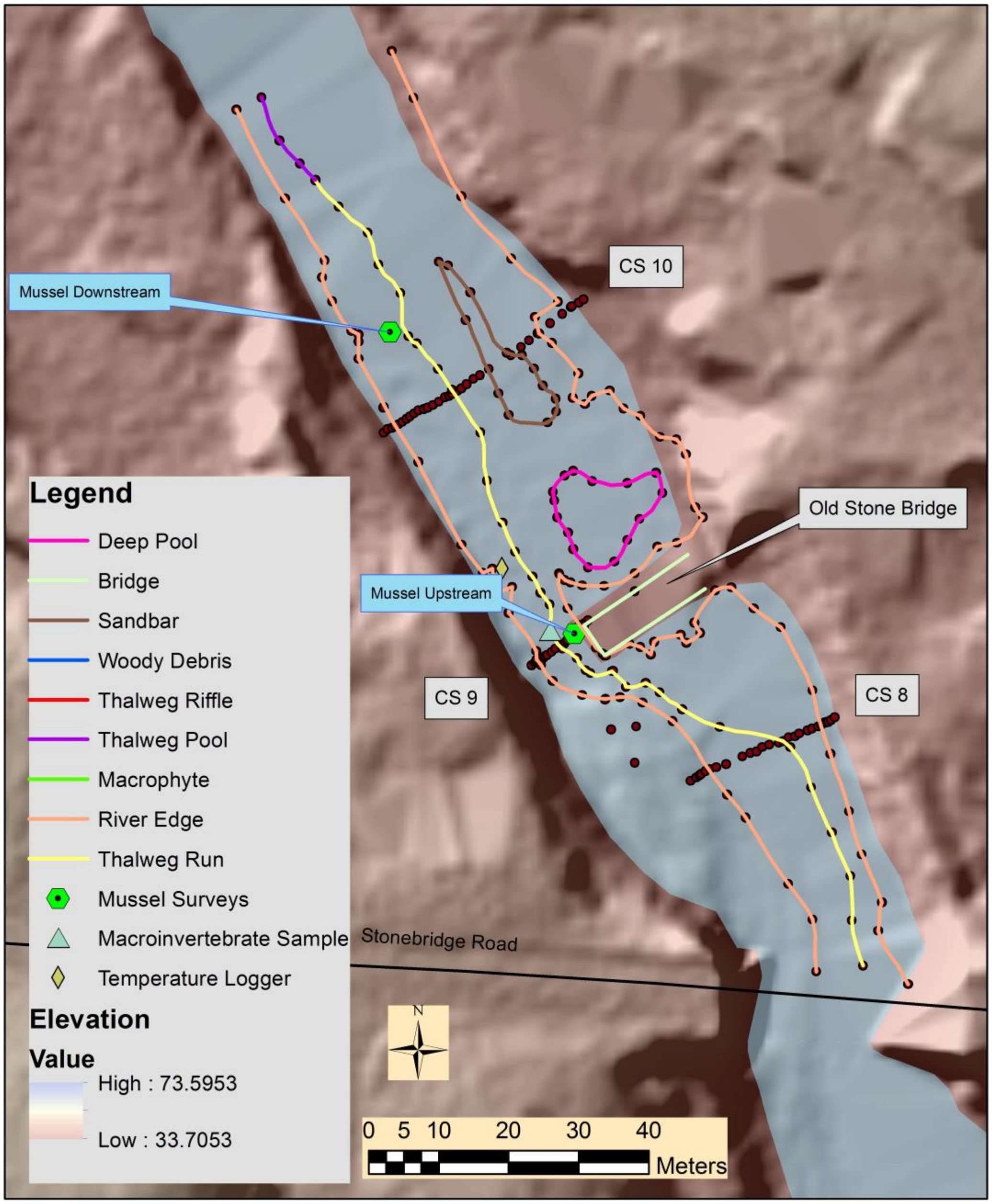

Figure A6 Survey data for Stone Bridge site. CS = cross section.

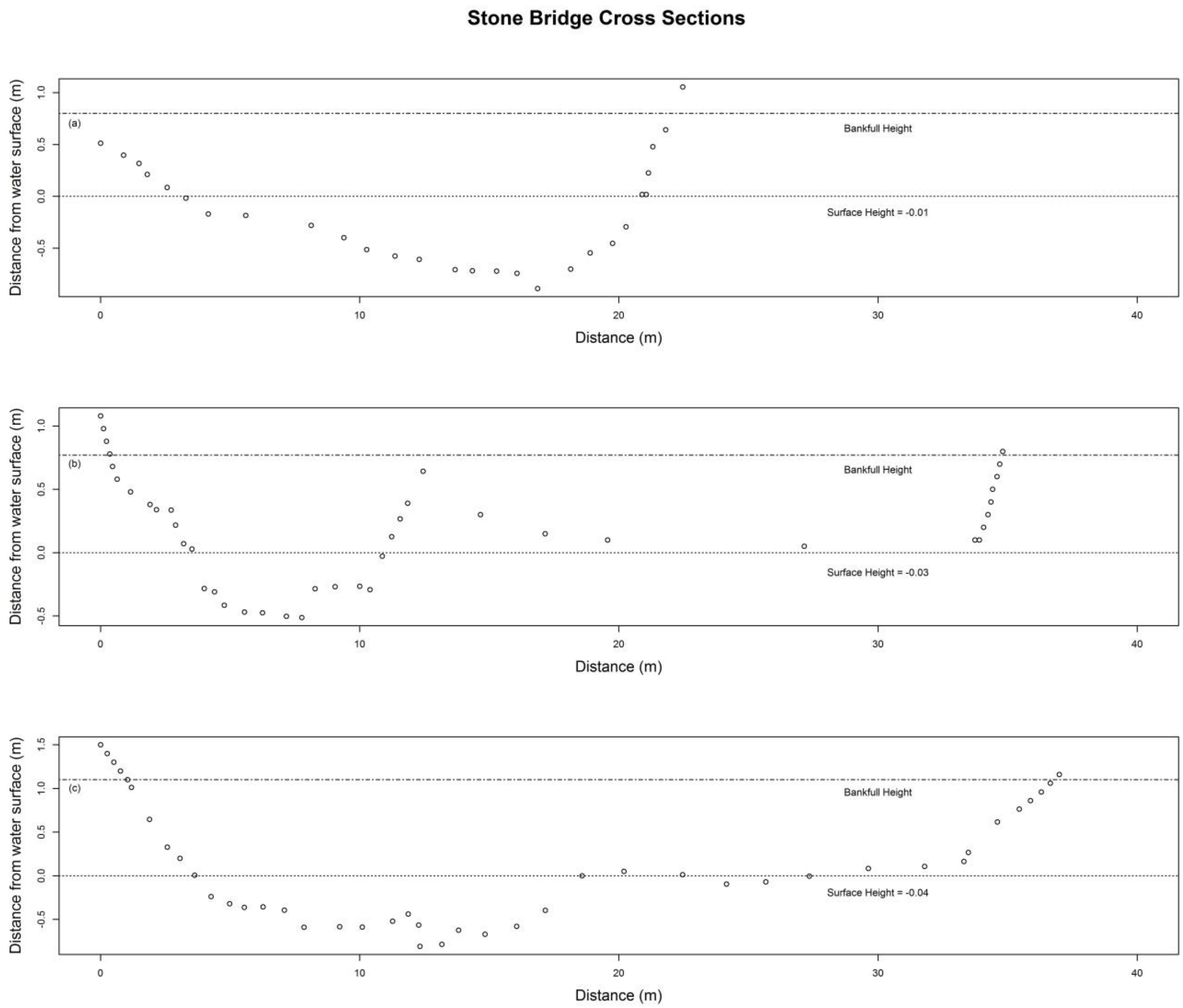

Figure A7 Profiles of a) cross section 8, slow run to pool habitat b) cross section 9, run habitat c) cross section 10, slow run habitat at Stone Bridge site. Cross sections are ordered 8-10 from upstream to downstream. Left side represents river left and right side represents river right. Surface height represents approximate height (m) at water surface relative to the top of the reach.

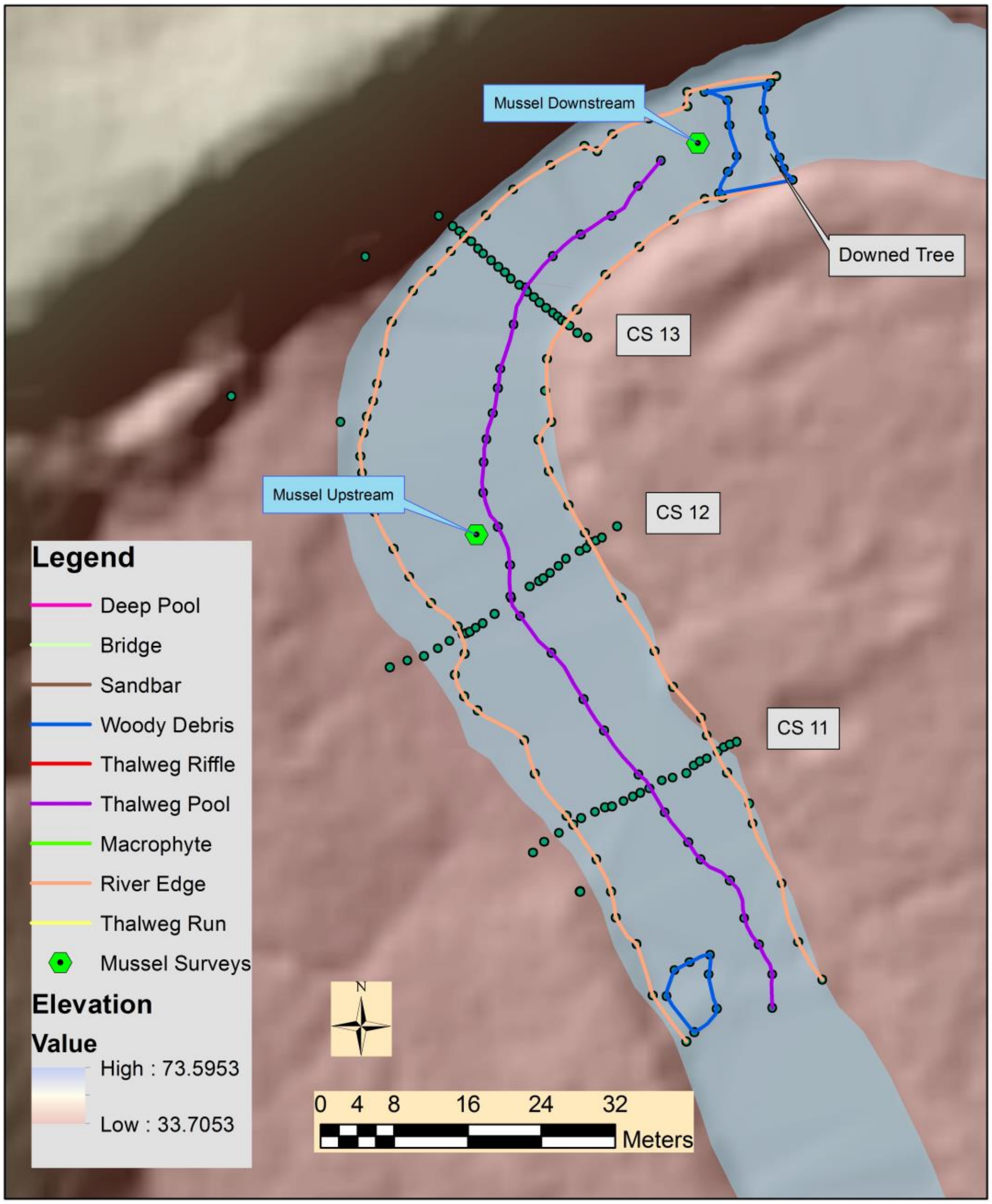

Figure A8 Survey data for River Bend Strainer site. CS = cross section.

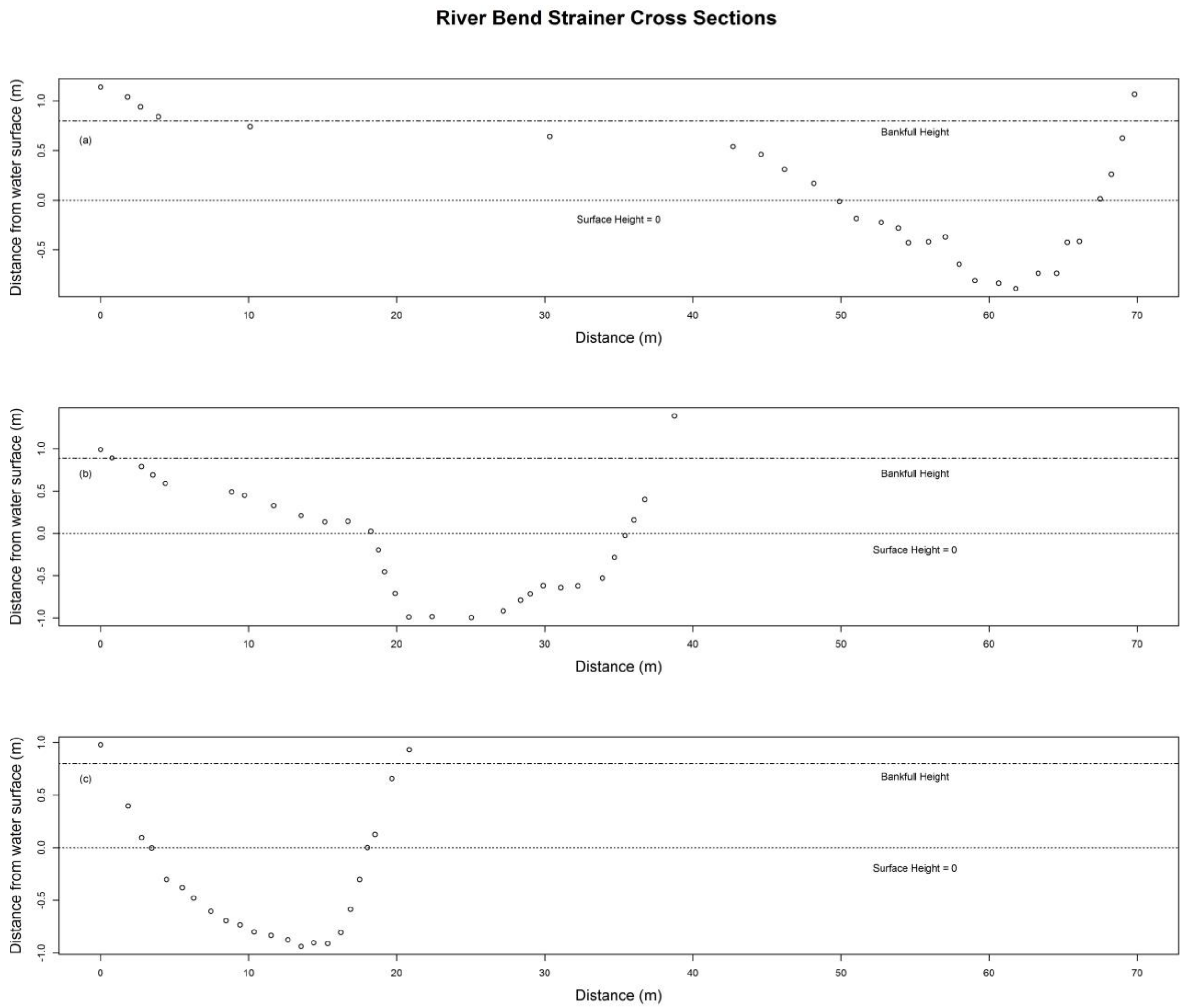

Figure A9 Profiles of a) cross section 11, pool habitat b) cross section 12, pool habitat c) cross section 13, pool habitat at River Bend Strainer site. Cross sections are ordered 11-13 from upstream to downstream. Left side represents river left and right side represents river right. Surface height represents approximate height (m) at water surface relative to the top of the reach.

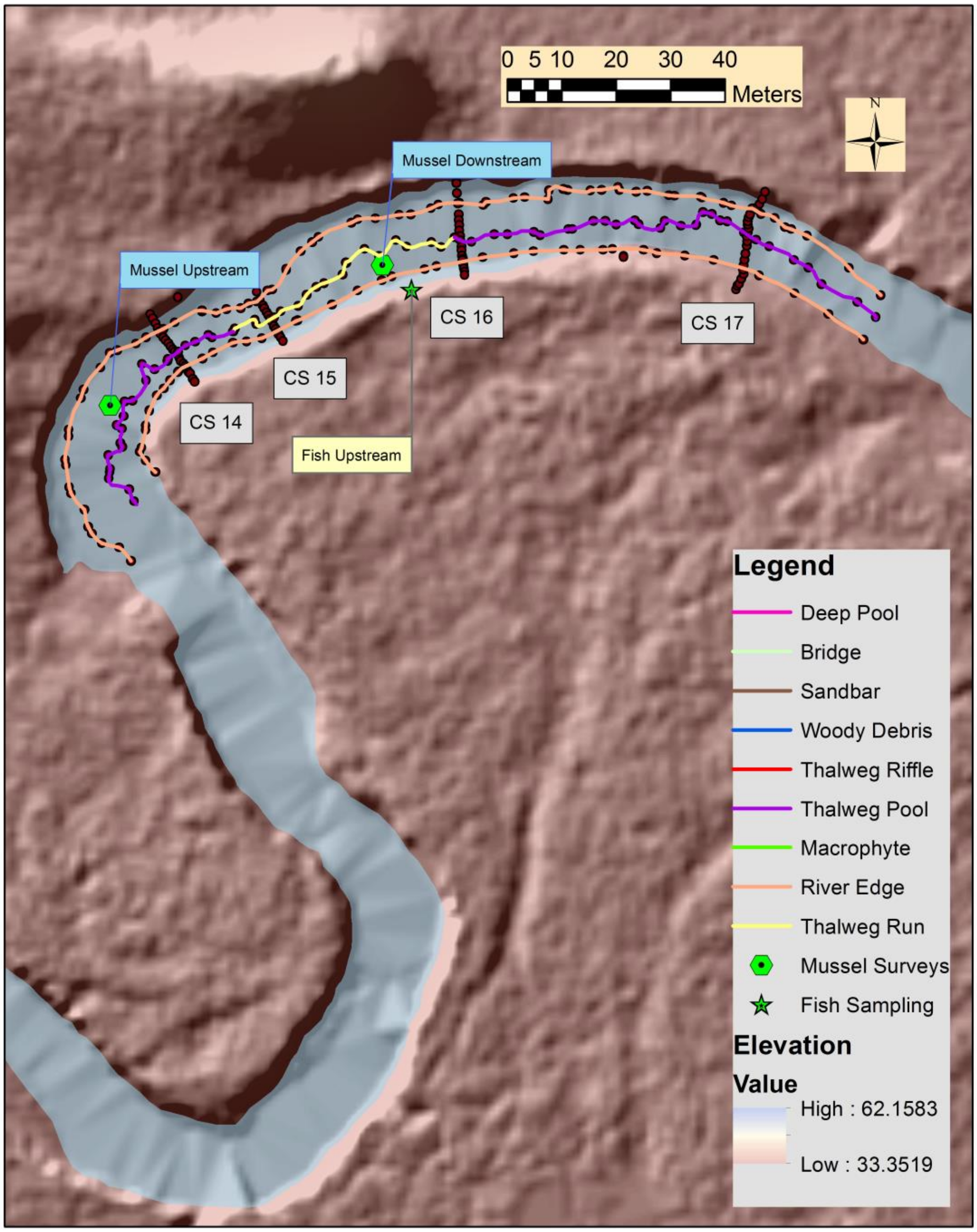

Figure A10 Survey data for Heard Pond Meander site. CS = cross section.

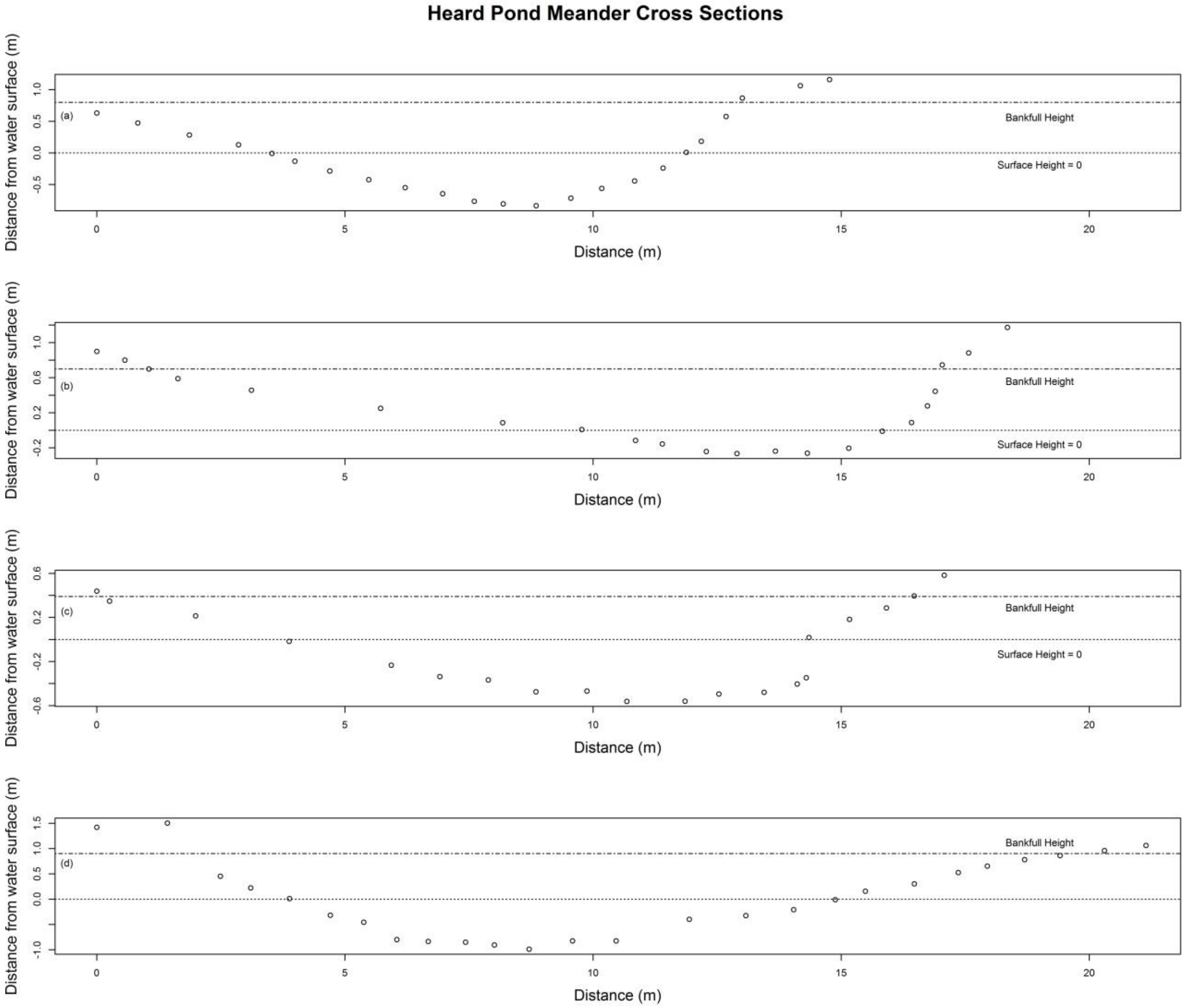

Figure A11 Profiles of a) cross section 14, pool habitat b) cross section 15, run habitat c) cross section 16, pool habitat d) cross section 17, pool habitat at Heard Pond Meander site. Cross sections are ordered 14-17 from upstream to downstream. Left side represents river left and right side represents river right. Surface height represents approximate height (m) at water surface relative to the top of the reach, where available.

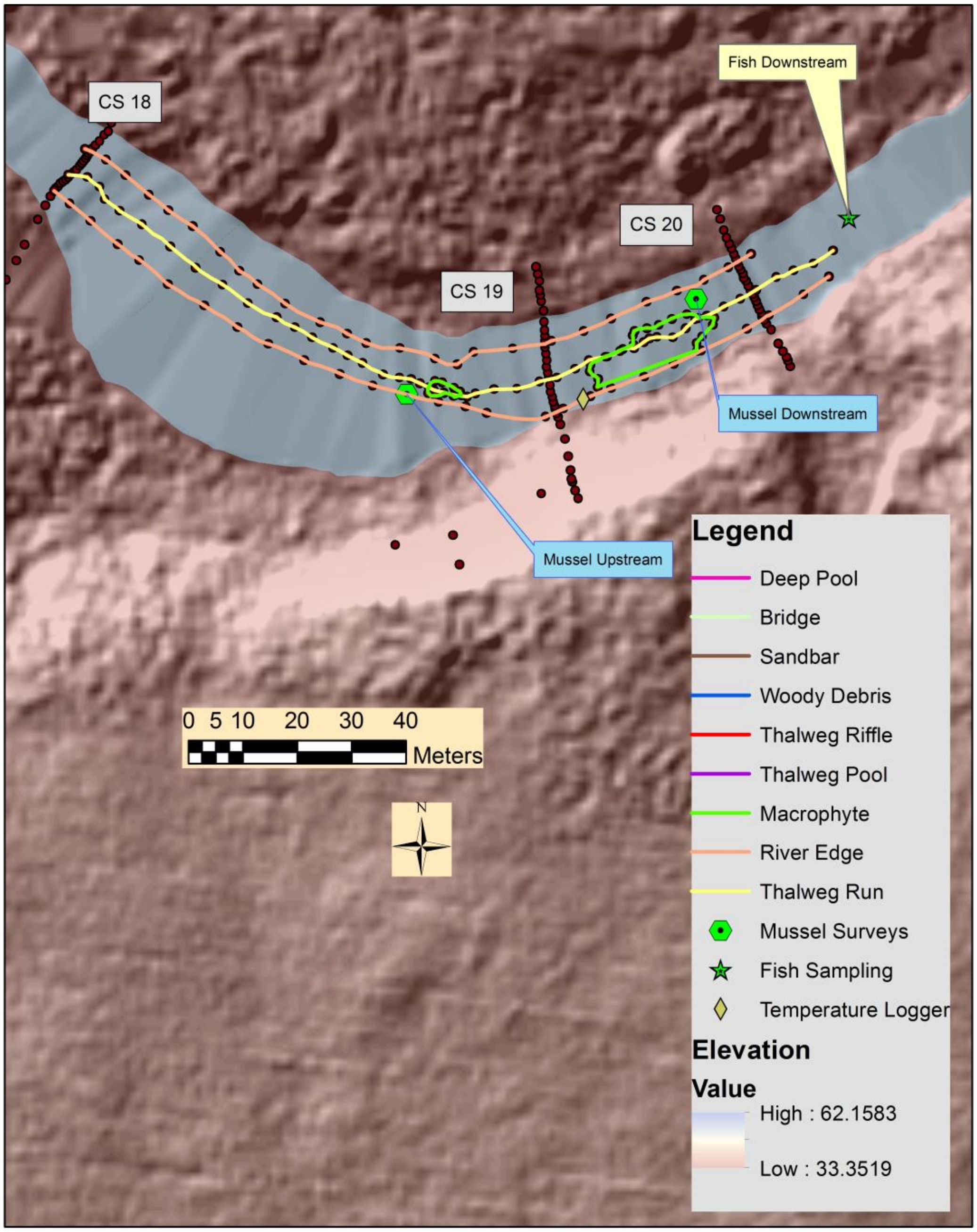

Figure A12 Survey data for Wayland High School site. CS = cross section.

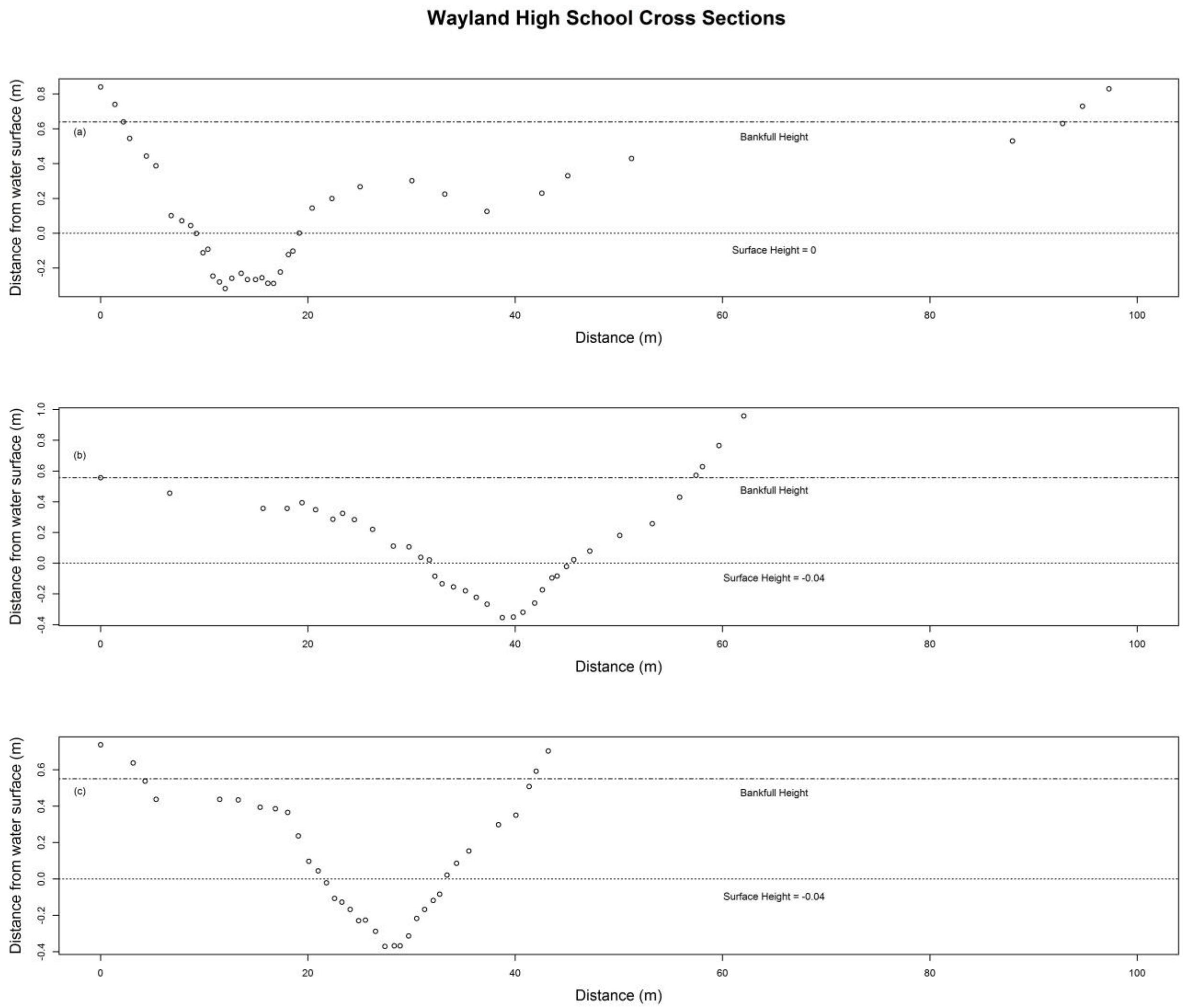

Figure A13 Profiles of a) cross section 18, slow run habitat b) cross section 19, slow run habitat c) cross section 20, run habitat at Wayland High School site. Cross sections are ordered 18-20 from upstream to downstream. Left side represents river left and right side represents river right. Surface height represents approximate height (m) at water surface relative to the top of the reach.

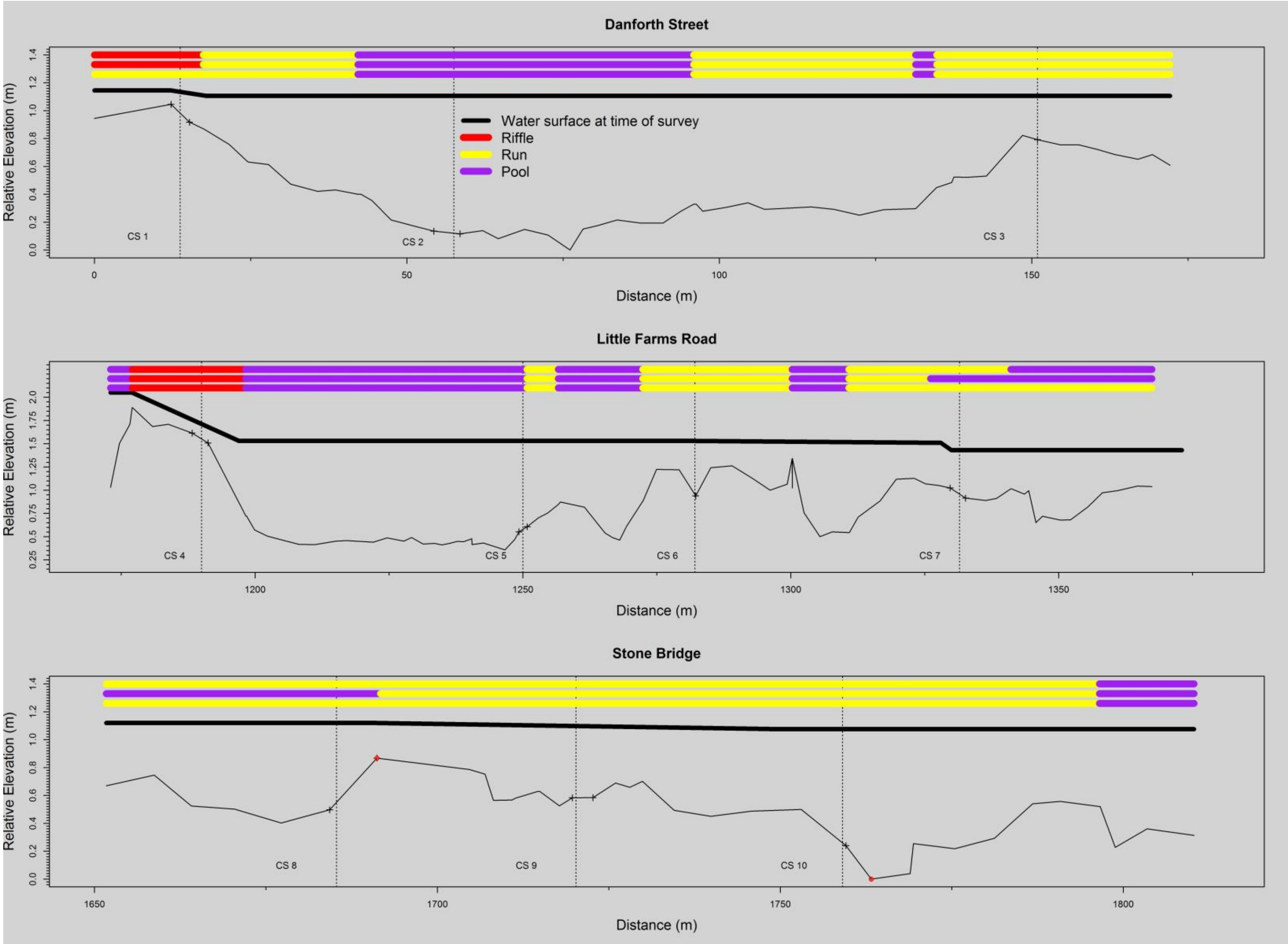

Figure A14 Longitudinal profiles of thalweg with habitat type shown as color coded horizontal bars. The top bar represents habitat type as determined during surveys, the middle bar represents modeled habitat at 6.2 cfs, and the bottom bar represents modeled habitat at 31.6 cfs.

Figure A15 Longitudinal profiles of thalweg with habitat type shown as color coded horizontal bars. The top bar represents habitat type as determined during surveys, the middle bar represents modeled habitat at 6.2 cfs, and the bottom bar represents modeled habitat at 31.6 cfs.

Table A4 Hydrologic parameters derived from IHA analysis of the Saxonville gage data of mean daily discharge from 1981 to 2013. Median, mean, minimum (min), and maximum (max) computed from annual data values derived from nonparametric analysis. Overall mean annual flow was 207.2 cfs. Note that a water year is considered to begin on October 1.

IHA Component	Units	Median	Coefficient of Dispersion	Mean	Min	Max
Group 1: Monthly Magnitude						
October	cfs	69.0	1.413	113.4	6.3	643.0
November	cfs	153.5	0.976	158.2	15.0	383.5
December	cfs	208.0	1.079	245.8	22.0	572.0
January	cfs	183.0	0.743	203.8	67.0	431.0
February	cfs	223.5	0.692	243.8	63.5	672.0
March	cfs	316.0	0.500	361.1	105.0	962.0
April	cfs	297.5	1.006	344.3	76.5	697.5
May	cfs	176.0	0.733	197.5	60.0	443.0
June	cfs	122.5	1.353	178.2	25.5	590.5
July	cfs	63.0	0.818	76.4	8.9	379.0
August	cfs	46.0	1.609	65.5	5.5	248
September	cfs	40.0	1.450	58.3	5.4	271.5
Group 2: Magnitude and duration of annual extremes						
1-day minimum	cfs	11.00	0.818	12.0	3.6	37.0
3-day minimum	cfs	12.00	0.968	13.6	3.7	39.7
7-day minimum	cfs	14.71	0.923	16.4	4.3	46.3
30-day minimum	cfs	32.37	1.024	33.1	7.1	109.9
90-day minimum	cfs	58.07	0.741	64.9	13.06	195.3
1-day maximum	cfs	977.0	0.458	1065.8	426.0	2440.0
3-day maximum	cfs	915.7	0.498	1003.0	405.3	2177.0
7-day maximum	cfs	856.9	0.466	878.3	298.6	1777.0
30-day maximum	cfs	565.0	0.532	565.0	143.8	1292.0
90-day maximum	cfs	380.6	0.387	391.6	124.2	710.8

IHA Component	Units	Median	Coefficient of Dispersion	Mean	Min	Max
Group 3: Timing of annual extremes						
Julian date of annual minimum	# of days after January 1	265	0.109	255	172	294
Julian date of annual maximum	# of days after January 1	116	0.383	155	28	360
Group 4: Frequency and duration of high and low pulses						
Low pulse count	NA	8	0.563	9	3	17
High pulse count	NA	9	0.333	8	1	17
Low pulse duration	days	5	0.700	6	2	19
High pulse duration	days	6	0.833	7	2	22
Group 5: Rate and frequency of change in conditions						
Fall rate	cfs/day	-12.0	-0.417	-11.7	-5.0	-20.5
Rise rate	cfs/day	19.0	0.763	20.6	7.0	43.0
Number of reversals	NA	108	0.102	107	96	124

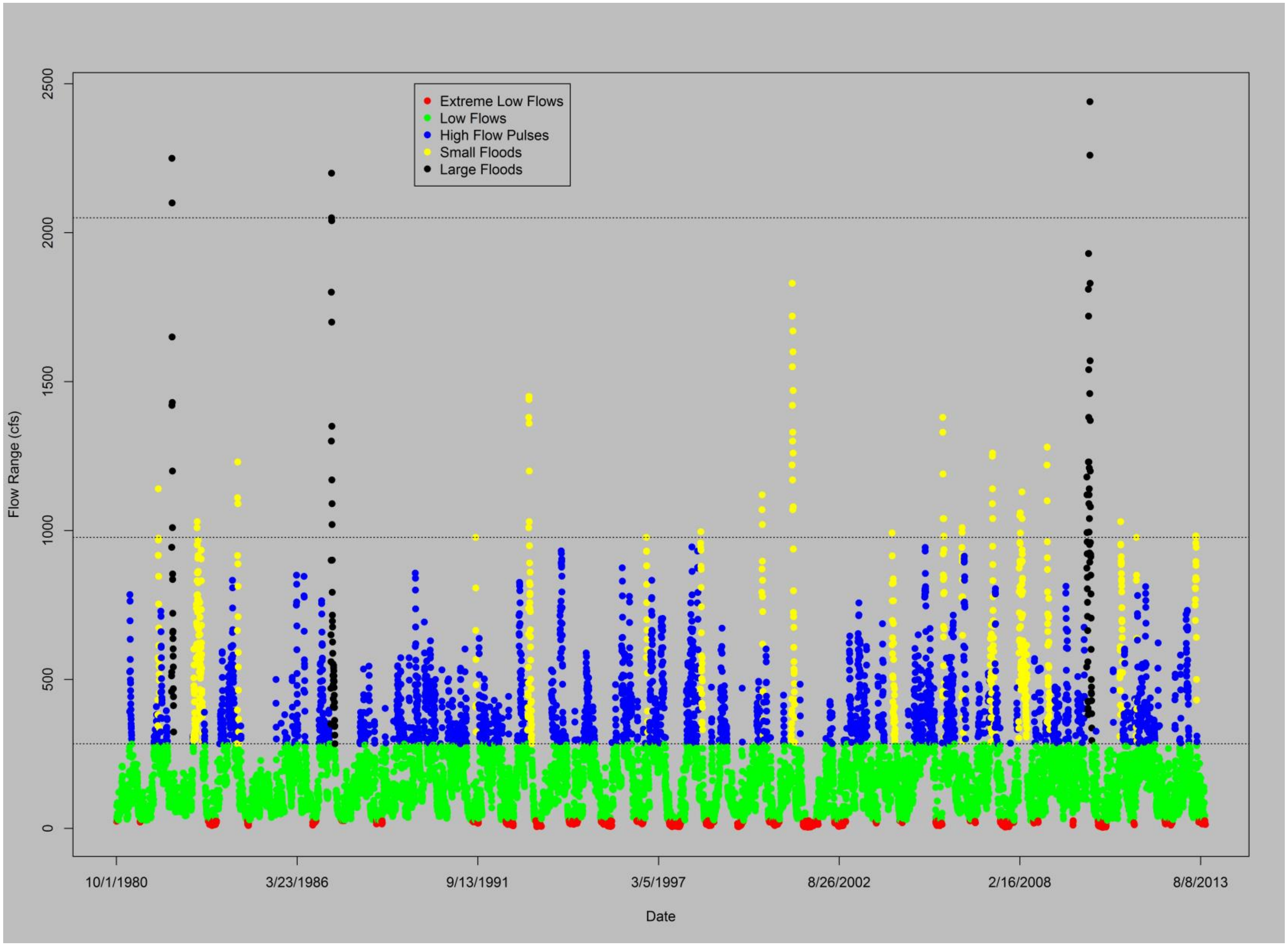

Figure A16 Environmental flow components for the Saxonville gage data. Each point represents the mean flow for one day.

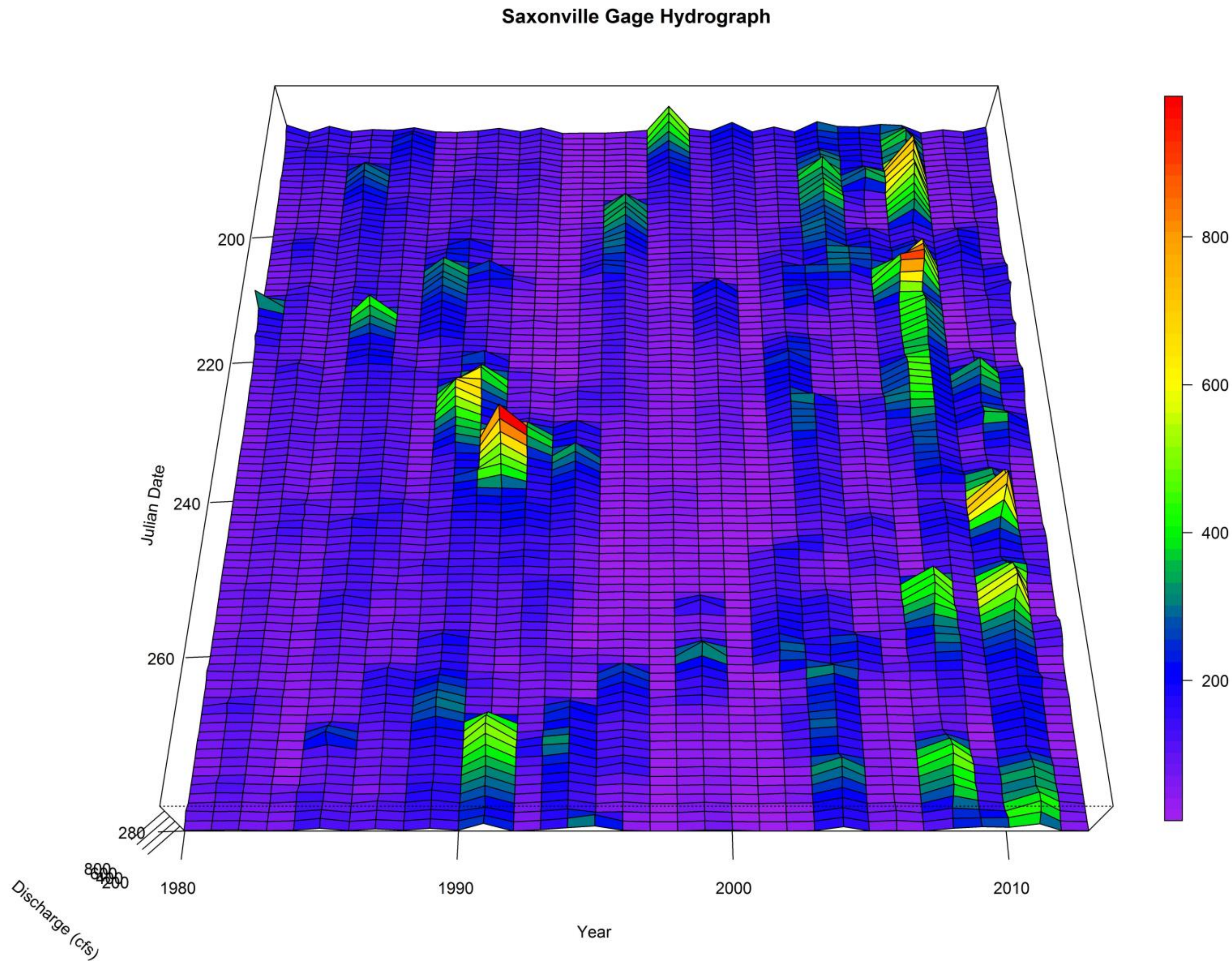

Figure A17 Hydrograph of Saxonville gage data for the low flow period between July 1 to October 7 of each year.

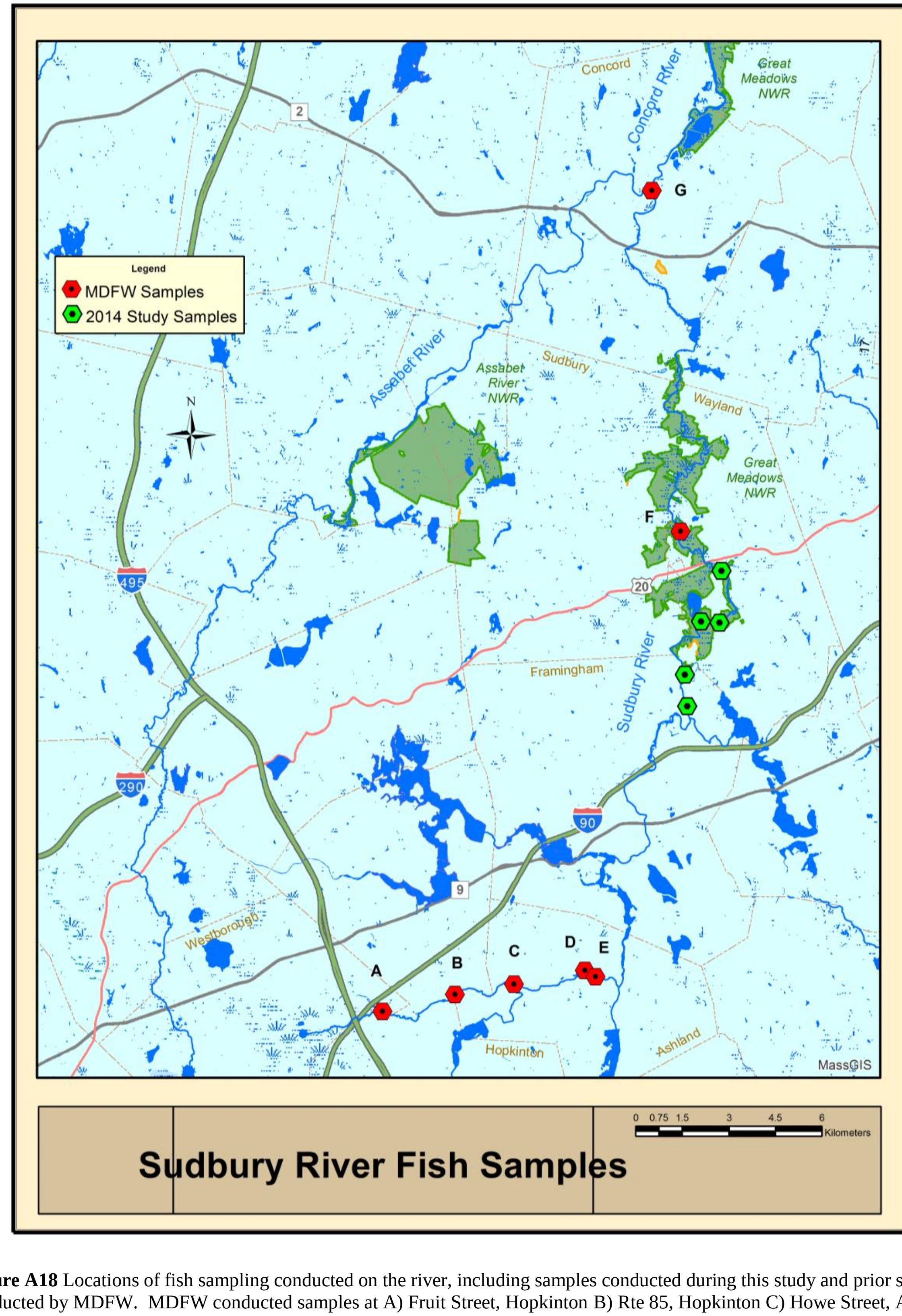

Figure A18 Locations of fish sampling conducted on the river, including samples conducted during this study and prior samples conducted by MDFW. MDFW conducted samples at A) Fruit Street, Hopkinton B) Rte 85, Hopkinton C) Howe Street, Ashland D) Myrtle Street, Ashland E) Concord Street, Ashland F) River Road, Wayland G) Lowell Road, Concord. See Table 8 for details of MDFW samples

Table A9 Locations and results of prior fish sampling conducted by the Massachusetts Division of Fisheries and Wildlife (MDFW). Three of these samples (ID 309, 310, and 399) were included in the Kashiwagi and Richards (2009) report for comparison to the TFC. Letters refer to map locations in Fig. 25.

Sample ID	311	399	4808	579	309	4807	310	4806	389	532
Location	Fruit Street, Hopkinton (A)			Rte 85, Hopkinton (B)	Howe St, Ashland (C)		Myrtle St, Ashland (D)	Concord St, Ashland (E)	River Rd, Wayland (F)	Lowell Rd, Concord (G)
Date	8/2/2001	7/31/2001	9/9/2013	7/31/2001	8/2/2001	9/9/2013	8/2/2001	9/9/2013	7/6/2001	7/5/2001
American eel									6	5
Black crappie									11	15
Bluegill		2		3	3	5	1	12	69	33
Brown bullhead		3							12	2
Chain pickerel					3		2		7	3
Common carp									10	16
Fallfish		3		23	14	24	53	23		
Golden shiner		1				1			37	1
Largemouth bass		2		6	12	15	10	1	41	13
Northern pike									2	1
Pumpkinseed		1			1	9	5	8	22	20
Rainbow trout	1									
Redbreast sunfish					16	11		15		
Redfin pickerel	34	114	15	5	1				6	
Rock bass				13			10			
White perch									8	3
White sucker	3		2	4	10	10	3		18	4
Yellow bullhead	4	1	14	2	4	8	8	3		
Yellow perch							9	3	187	72
Total abundance	42	127	31	56	64	83	101	65	436	188