July 2017

Accounting For Biotic Variability In Streams With Low Levels of Impervious Cover: The Role of Reach- and Watershed-Scale Factors

Catherine Bentsen

University of Massachusetts Amherst

Recommended Citation

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Accounting For Biotic Variability In Streams With Low Levels of Impervious Cover: The Role of Reach- and Watershed-Scale Factors

A Thesis Presented

by

CATHERINE NICOLAISEN BENTSEN

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

May 2017

Environmental Conservation

Accounting For Biotic Variability
In Streams With Low Levels of Impervious Cover:
The Role of Reach- and Watershed-Scale Factors

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Approved as to style and content by:

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Allison H. Roy, Chair

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Rachel A. Katz, Member

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Christine E. Hatch, Member

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Curt R. Griffin, Department Head
Department of Environmental Conservation

DEDICATION

For my Dad:

although you are no longer here in person, you are always with me in spirit

ACKNOWLEDGMENTS

This work would not have been possible without the tremendous support and guidance provided by my advisor, Allison Roy. Allison has been invaluable in navigating the challenges of research and honing a large swath of information into a coherent storyline. Her countless hours spent providing timely and critical feedback have successively improved my work, which I hope is adequately reflected in this thesis. My committee members, Rachel Katz and Christine Hatch, provided valuable insights throughout the process, particularly related to analyses, framing, and perspective.

This thesis is one component of a larger project, for which I am indebted to the other project team members. Dave Armstrong at USGS New England Water Science Center in particular guided the project through its various stages, organizing multiple team members for regular meetings and conference calls, and wrangling a large dataset that I have been fortunate to use in my own work. Dave was also a huge help in the field, providing guidance on field methodology as well as helping me get up to speed on surveying with the electronic total station. Lance Ostiguy and Sara Levin at USGS were important contributors to this dataset, as was Matt Baker at University of Maryland Baltimore County.

Massachusetts Department of Environmental Protection (MDEP) and Massachusetts Division of Fisheries and Wildlife (MDFW) were vital state partners. MDEP provided funding for this project, and both MDEP and MDFW contributed the rich biotic datasets on which this project was built. Bob Nuzzo at MDEP served as invaluable macroinvertebrate expert, who generously lent expertise on the extensive macroinvertebrate data collected by MDEP and their numerous staff and technicians who collected, sorted, and identified hundreds of bug samples over the years. Cole Ecological, Inc., under leadership from Michael Cole, provided timely and accurate macroinvertebrate identification for additional bug samples I collected. Similarly, staff at MDFW, especially Todd Richards, Jason Stolarski, and Leanda Fontaine Gagnon provided expertise, data sharing, and additional field sampling along with their regional fish sampling crews. Todd, also a member of the Roy lab group, asked key questions regarding data collection, analysis, and interpretation.

At University of Massachusetts Amherst, the Roy lab served as my intellectual home for all things aquatic. Bob Smith, a member of the Roy lab and project partner, contributed significant time to discuss analytical methods, give feedback on presentations, and hash out ideas about theoretical and applied ecology. Expert GIS guidance from Bob allowed me to dive directly into site selection shortly after starting grad school. Lab group meetings provided commentary to improve and interpret analyses, posters, and presentations. Lab get-togethers off campus were equally important in providing work-life balance during the grad school process. Many members of the Roy group have been part of the lab for the entire or partial duration of my tenure at UMass Amherst, including postdocs Bob Smith, Rachel Katz, and Sean Sterrett; fellow grad students Emily Argo, Meghna Marjadi, Julianne Rosset, Todd Richards, Jason Carmignani, Matt Devine, Peter Zaidel, and Steven Mattocks; and honors undergraduates Allyson Yarra and Chris Smith.

My fieldwork would not have been possible without the dedication and long hours undertaken by undergraduate technicians. Chris Smith and Ben Knicely were my main technicians during summers of 2014 and 2015, respectively, although numerous other graduate and undergraduate students spent time in the field helping me survey, measure discharge, and collect water quality samples. The Massachusetts Cooperative Fish and Wildlife Research Unit has incredible administrative support through Deb Wright. The Coop Unit generously provided vehicles for fieldwork, on which I put thousands of miles traveling around the state, hauling truckloads of gear to my sites. I thank all of the towns and private landowners who granted me access through their land to sample stream sites over the course of my thesis.

I would be remiss not to mention the constant support and encouragement of my family and friends to get me through the hurdle of grad school. I am looking forward to having more time to spend with all of you once this chapter—pun intended—is complete.

ABSTRACT

ACCOUNTING FOR BIOTIC VARIABILITY IN STREAMS WITH LOW LEVELS OF IMPERVIOUS COVER: THE ROLE OF REACH- AND WATERSHED-SCALE FACTORS

MAY 2017

CATHERINE N. BENTSEN, B.S. CORNELL UNIVERSITY

M.S. UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Allison H. Roy

As landscapes become increasingly urbanized, there is an associated increase in impervious cover. Impervious surfaces, such as roads, rooftops, and parking lots contribute to the physical, hydrological, chemical, and biological alteration of stream systems. Biotic assemblages consistently degrade with increased watershed impervious cover; however, at low levels of impervious cover, these assemblages exhibit wide variability in biotic integrity. This study investigated which reach- and watershed-scale factors explained biotic condition (i.e., richness, flow traits, thermal traits, and tolerance for macroinvertebrates and fishes) at similar levels of low imperviousness. The primary objective was to identify factors that confer resistance for biota, such that they retain high biotic integrity at low levels of impervious cover, and, conversely, to determine which factors make biota more vulnerable to urban disturbance, such that they have low biotic integrity despite low levels of impervious cover. Forty sites were selected across Massachusetts within two narrow bands of impervious cover: 1–4% (*n* = 20) and 7–10% (*n* = 20). Models with reach-scale variables (reflecting habitat heterogeneity, flow, temperature, or water quality) or watershed-scale variables (representing natural characteristics, land use, flow alterations, and other measures of urbanization or impervious) explained additional variance compared to models with impervious cover alone. Reach-scale factors tended to explain more variance than watershed-scale factors for all biotic responses except fluvial fishes, with overall more variance explained for fish than macroinvertebrate assemblages. At the reach scale, colder water temperatures, higher dissolved oxygen, and more large wood were related to higher proportions of fluvial, coldwater, and intolerant fishes. For macroinvertebrates, warmer water temperature, smaller sediment size, and higher nitrate were related to higher macroinvertebrate richness and tolerance. At the watershed scale, air temperature emerged as an important predictor for both taxonomic groups and across response metrics; air temperature was highly correlated with high-elevation watersheds. Other important watershed-scale predictors were open water and dams, flow alteration, and other urban measures such as housing density, impervious in a 120-m buffer, and road crossings. Restoration should focus on strategies to reduce impacts that would degrade in-stream conditions that allow for higher biotic integrity, such as habitat heterogeneity, more large wood, and colder water temperatures. Similarly, watersheds should be prioritized for protection with those characteristics potentially more resistant to urban disturbance, such as high-elevation regions that retained high biotic integrity despite higher dam density, more road crossings, and more flow alteration.

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CHAPTER 1

INTRODUCTION

1.1 Urbanization patterns and processes

In 2014, more than half (54%) of the global population lived in urban compared to rural areas (United Nations 2015). Urbanization is projected to increase globally, with 66% of the population expected to live in urban areas by 2050 (United Nations 2015). In the United States, as of 2012 81% of the populace lived within urban areas (towns/cities with more than 50,000 people), an increase from 79% in 2000 (U.S. Census Bureau 2012) and 72% in 1950 (Brown et al. 2005). The Northeast is one of the mostly highly urbanized regions of the United States (U.S. Census Bureau 2012), reflected in the highly urbanized corridor connecting the major metropolitan areas spanning from Washington, DC to Boston, MA.

As the urban population has increased, so has the amount of developed land. In 1950, 1% of the conterminous United States was classified as higher-density urban land (>1 housing unit per 0.4 ha) and 5% as lower-density exurban land (1 unit per 0.4–16.2 ha), with the remaining classified as rural (<1 unit per 16.2 ha). By 2000, urban land had increased to 2% land area and exurban land jumped to 25% as the population shifted from cities to suburbs (Brown et al. 2005).

Urban areas exert a disproportionate effect on the landscape, despite occupying a relatively small amount of total land (Allan 2004). Urbanization fragments the mosaic of land cover, increasing edges and patch sizes (Grimm et al. 2008). Cities alter climatic and biogeochemical cycles by creating greenhouse gases, elevating air and surface temperatures (i.e., urban heat island effect), inputting air and water pollutants, creating waste, and altering decomposition (Grimm et al. 2008). The urban heat island effect, or the difference between urban and rural temperatures, is most pronounced during nighttime and is influenced by vegetation, building materials and pavement, human energy use, city size, and population density, with subsequent implications for vegetation phenology and soil temperature and moisture (Pickett et al. 2011). Natural vegetation in urban areas is replaced with lawn, ornamental, and horticultural vegetation that also changes soil organic matter and moisture (Groffman et al. 2014), as well as evapotranspiration in the hydrological cycle. The combination of altered microclimate, biogeochemical cycles, and natural vegetation, as well as human preferences based on socioeconomics and lifestyle, creates conditions such that cities are more similar to one another than to their natural context in terms of ecosystem structure and function (Groffman et al. 2014).

1.2 Urban stream syndrome: abiotic responses

Stream systems integrate the conditions of the landscapes through which they flow (Hynes 1975, Allan 2004). Urbanization impacts on lotic systems have been well documented (see syntheses: Paul and Meyer 2001, Walsh et al. 2005, Wenger et al. 2009) and collectively termed the ‘urban stream syndrome’ (Meyer et al. 2005, Walsh et al. 2005). Total impervious surface area is one metric commonly used to quantify the extent of urbanization in a watershed (Schueler 1994, Arnold and Gibbons 1996), as it is more significantly related to stream condition than measures of overall urban land (Wang et al. 2001, Brabec et al. 2002). Impervious surfaces are those areas of the landscape that prevent infiltration of water into the soil, such as roads, rooftops, parking lots, and compacted soil (Arnold and Gibbons 1996). Reduced infiltration leads to higher volume and velocity of surface runoff that is delivered more rapidly to the stream channel after precipitation events, corresponding to flashier stream hydrographs in catchments with higher impervious cover (Leopold 1968, Graf 1977, Klein 1979, Booth and Jackson 1997, Paul and Meyer 2001, Roy et al. 2005, Poff et al. 2006a). These higher peak flows typically alter stream geomorphology by scouring stream banks, widening and incising the streambed, and transporting and depositing higher sediment loads (Booth and Jackson 1997, Hession et al. 2003, Chin 2006, Hawley et al. 2013). Stream channels are directly modified through straightening, channelizing, or burying streams in pipes and culverts (Elmore and Kaushal 2008).

Urbanization also affects water quality. Chemical contaminants enter streams via stormwater runoff (Paul and Meyer 2001, Brabec et al. 2002, Kaushal et al. 2005) and leaky wastewater infrastructure and septic systems (Kaushal and Belt 2012). Concentrations of nitrogen, phosphorus, chloride, heavy metals, organic contaminants, and bioavailable organic carbon and nitrogen are elevated in urban streams compared to their forested counterparts (Pickett et al. 2011). The interaction of altered hydrology and incised stream channels affects nutrient processing, uptake, and longitudinal transport (Pickett et al. 2011). Water that runs off impervious surfaces bypasses infiltration to groundwater and the subsequent biogeochemical reactions (e.g., denitrification) that typically occur within the upper soil layers in riparian zones (Groffman et al. 2002).

Removal of riparian vegetation in conjunction with urban development decreases canopy cover as well as the amount of large wood in the channel (Finkenbine et al. 2000). Reduced canopy shading, compounded by the urban heat island effect, results in higher stream temperatures in urban compared to forested streams, particularly during base flow (Paul and Meyer 2001, Pickett et al. 2011) but also during storm flows (Somers et al. 2013).

The convergent effects of urbanization are found in both terrestrial and aquatic systems. For instance, surface waters across the United States have become more similar to one another compared to the surrounding landscape due to hydrographic alteration (Groffman et al. 2014, Steele et al. 2014). Waterbody size has converged, waterbody shorelines have simplified, and the number and area of waterbodies intersecting rivers have decreased (Steele and Heffernan 2014).

1.3 Urban stream syndrome: biotic responses

The physical, hydrological, and chemical alteration of streams and their watersheds resulting from increased development and impervious cover subsequently influences the biological assemblages found in urban streams. As the spatial extent of impervious surfaces increases in a watershed, biotic communities often degrade. Benthic macroinvertebrate assemblages have lower richness and diversity in urban streams compared to either forested streams (Klein 1979, Roy et al. 2003) or agricultural streams (Moore and Palmer 2005, Smith and Lamp 2008). As a result of urbanization, the presence of sensitive macroinvertebrates declines, often measured by EPT (Ephemeroptera, Plecoptera, Trichoptera) richness (Cuffney et al. 2010) or multimetric indices of biotic integrity (Morley and Karr 2002). Other metrics of macroinvertebrate sensitivity, such as presence of predators or long-lived taxa, also decline in response to watershed urbanization (Morley and Karr 2002). These macroinvertebrate responses are potentially attributable to urban-induced hydrological flashiness (Morley and Karr 2002), flow fluctuations (Konrad and Booth 2005), substrate roughness (Morley and Karr 2002), sedimentation (Roy et al. 2003), chemical contamination (Morgan et al. 2007), or thermal stress (Somers et al. 2013).

Fish communities also respond detrimentally to increased urbanization and impervious cover. Fish assemblages generally have lower diversity (Klein 1979), lower community health and indices of biotic integrity (Wang et al. 1997, Snyder et al. 2003), fewer sensitive and more tolerant fish species (Morgan and Cushman 2005, Roy et al. 2005), fewer endemic species (Meador et al. 2005), and fewer fluvial specialists (Meador et al. 2005, Armstrong et al. 2011). Species assemblages also tend to shift from those associated with riffle habitats and coarse substrate to those associated with slow-water habitats and no substrate preference (Brown et al. 2009). Although fish species richness typically declines in relation to urbanization, some regions may experience increased fish richness due to more tolerant native species as well as introduction of invasive species (Meador et al. 2005). Armstrong et al. (2011) found that impervious cover, flow alteration, and alteration of August median flow from groundwater withdrawals were related to lower species richness as well as abundance of fish fluvial specialists in Massachusetts streams.

Most urban studies demonstrate that biotic communities degrade along a gradient of increasing urbanization or impervious cover (Carter et al. 2009). Schueler et al. (2009) conceptualized this response as a cone that progressively narrows as impervious cover increases in a watershed (Figure 1.1). While biotic communities are commonly degraded at higher levels of impervious cover, biotic integrity still varies widely at lower levels of impervious cover. According to this model, streams with the same, low level of impervious cover exhibit different responses: some sites have high biotic condition (e.g., high richness or diversity, more sensitive species), while other sites have degraded biotic condition (e.g., low richness or diversity, more tolerant species). Few studies have examined evidence for different mechanisms driving this high variability in low-level urban streams.

1.4 Biotic variability at low levels of impervious cover

This thesis seeks to determine factors that explain differences in biotic condition observed across sites with similar levels of low impervious cover. The overarching aims of this study are to assess which reach-scale physicochemical and habitat factors (Chapter 2) and watershed-scale landscape factors (Chapter 3) best explain macroinvertebrate and fish assemblages across sites with similar levels of watershed impervious cover.

The impetus for this research builds on a body of work conducted on water resources and biotic communities in Massachusetts. In 2010, the Massachusetts Executive Office of Energy and Environmental Affairs initiated the Sustainable Water Management Initiative (SWMI) with the intention of managing water allocations and permitting withdrawals, as mandated by the Water Management Act of 1987 (MA EOEEA 2012). Water allocations are to be made with regard to both safe yield and streamflow criteria. Safe yield refers to the amount of water available to be withdrawn during drought conditions and traditionally refers to a single annual value. For permitting water withdrawals in Massachusetts, safe yield is approximated by sustainable yield, a time-varying value determined with the Sustainable Yield Estimator (SYE), a tool developed for simulating streamflows for ungaged stream sites in Massachusetts by Archfield et al. (2010). The SYE output is the monthly 'sustainable yield' volume, which is the maximum volume of water that can be withdrawn without depleting a steam lower than a user-specified value (i.e., the target streamflow value). Streamflow criteria incorporate the magnitude and timing components of the natural flow regime.

As part of SWMI, a collaborative effort among the U.S. Geological Survey (USGS), Massachusetts Department of Conservation and Recreation (MDCR), Massachusetts Department of Environmental Protection (MDEP), and the Massachusetts Division of Fisheries and Wildlife (MDFW) was established to elucidate factors affecting fluvial fish assemblages in Massachusetts (Armstrong et al. 2011). Armstrong et al. (2011) found that increases in alteration of August median flow from groundwater withdrawals, increases in flow alteration indicators, and increases in impervious cover were related to decreases in fluvial specialist abundance and species richness (Armstrong et al. 2011). Statistical models developed to explain fluvial fish species richness and abundance and brook trout relative abundance all included impervious cover, among other variables. The significant finding of alteration of August median flows was incorporated into streamflow criteria for SWMI. Groundwater control levels and biological categories related to tiers of fluvial fish condition were also developed based on findings in the report (MA EOEEA 2012). The significant finding of the relationship between impervious cover and fish assemblages in Massachusetts provided the basis for a new, collaborative effort among MDEP, MDFW, USGS New England Water Science Center, and Massachusetts Cooperative Fish and Wildlife Research Unit at the University of Massachusetts Amherst. This project built on previous work while leveraging the extensive monitoring datasets collected by MDEP and MDFW for macroinvertebrates and fishes across the state. The wealth of information available in these biotic databases was used to explore questions about the relationship between watershed variables and aquatic biota along a gradient approach of impervious cover.

My thesis differed from the larger project in two main ways. First, I used a subset of sites from the biotic databases to limit the range of impervious cover to two narrow bands. By constraining the level of impervious, this allowed me to focus on other factors that drive variability in addition to total impervious cover. Second, I conducted an intensive study of variables manifested at the reach scale; data that are often correlated with aquatic assemblages, but are not necessarily collected during large-scale, long-term monitoring efforts. The results of this study contribute to a greater understanding of the urban stream syndrome and its nuances at lower levels of impervious cover, where variation in natural and anthropogenic factors play a potentially important role in determining which biotic assemblages are present. The implications of these results for management decisions made across the state and region are discussed in Chapter 4.

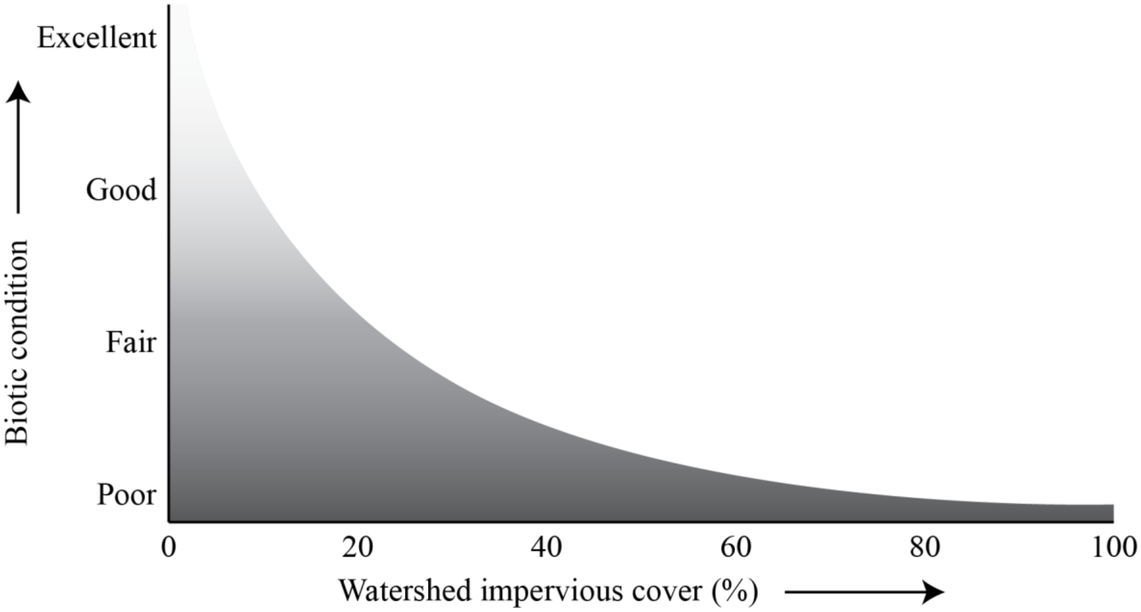


Figure 1.1. Conceptual diagram of the generalized relationship between impervious cover and biotic condition: as watershed imperviousness increases, biotic condition degrades. Biotic assemblages exhibit wide variability at low levels of impervious cover, however, likely due to variation in reach- and watershed-scale factors. Diagram modified from Schueler et al. (2009).

CHAPTER 2

PHYSICOCHEMICAL CHARACTERISTICS EXPLAIN DIFFERENCES IN BIOTIC RESPONSES TO URBANIZATION

2.1 Introduction

The United States is highly urbanized: 81% of the population lives in urban areas of more than 50,000 people (U.S. Census Bureau 2012), and the percent urban land is projected to continue to rise. The presence and extent of urbanization on the landscape, as typically characterized by total percent impervious cover in the catchment (Arnold and Gibbons 1996), subsequently influences aquatic resources. Watersheds with higher levels of impervious cover have flashier hydrology (Leopold 1968, Graf 1977, Klein 1979, Booth and Jackson 1997, Paul and Meyer 2001, Roy et al. 2005, Poff et al. 2006a), altered channel geomorphology (Booth and Jackson 1997, Hession et al. 2003, Chin 2006, Hawley et al. 2013), and higher chemical contaminant loads (Paul and Meyer 2001, Brabec et al. 2002, Kaushal et al. 2005, Kaushal and Belt 2012) compared to their non-urbanized counterparts. In turn, macroinvertebrate and fish assemblages generally show lower richness, lower diversity, fewer sensitive taxa, and more tolerant taxa as watershed impervious cover increases (Paul and Meyer 2001, Morley and Karr 2002, Roy et al. 2003, Morgan and Cushman 2005, Walsh et al. 2005).

Despite the generally consistent declines in biotic integrity with increasing urbanization, biotic condition is highly variable across sites, particularly at low levels of impervious cover. In a Maryland study, for example, macroinvertebrate benthic index of biotic integrity (B-IBI) and Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa richness exhibited the greatest ranges at the lowest levels of impervious surface area (<5 or 10%) in each of the Coastal Plain, Piedmont, and Highlands physiographic regions (Goetz and Fiske 2008). Although Collier and Clements (2011) found a declining trend for four macroinvertebrate metrics (i.e., taxa richness, EPT taxa, an Urban Community Index, and quantitative UCI derived from tolerance values) along a gradient of impervious area, the authors noted considerable scatter among sites for each metric, particularly at low levels of impervious surface. For fishes, index of biotic integrity values ranged widely in both Coastal Plain and Piedmont physiographic regions of Maryland, especially when catchment urbanization was less than 25% (Morgan and Cushman 2005). In Massachusetts, Armstrong et al. (2011) showed how impervious cover limited fish richness and fluvial fish abundance, with the most variance occurring at the lowest levels of impervious cover.

A synthesis of numerous studies that showed similar patterns of biotic degradation with urbanization led to the development of the impervious cover model by Schueler (1994), which was later refined with additional studies in Schueler et al. (2009). The impervious cover model depicts a cone or wedge that progressively narrows as total impervious cover increases in the watershed, with stream quality subsequently degrading. While stream quality, including biotic condition is consistently degraded at high levels of impervious cover, stream condition ranges from poor to excellent at sites with low levels of impervious cover. Schueler et al. (2009) suggested that other factors in addition to impervious cover are likely useful for explaining the variability found in watersheds with low impervious cover.

The concept of variability is not new to stream ecology: several decades of theoretical and experimental work (reviewed by Winemiller et al. 2010) have demonstrated that ecosystems vary across space and time due to the complex interplay of disturbance history, abiotic environmental characteristics, and biotic interactions (Townsend 1989, Poff and Ward 1990, Palmer and Poff 1997, Fraterrigo and Rusak 2008, Stanley et al. 2010). As the extent of urbanization or impervious cover increases in a watershed, the combined effects from increased frequency, magnitude, and intensity of urban-induced disturbances (e.g., altered hydrology, contaminant pulses) likely suppress the physical, chemical, and biological variability that might otherwise occur naturally in the system. As such, the nature and magnitude of effects induced by watershed urbanization manifest differently based on local and regional variation (Booth et al. 2016), including variation of the underlying environmental template. The physical habitat template proposed by Poff and Ward (1990) examines substratum-geomorphologic characteristics, streamflow, and thermal characteristics, to which we add water chemistry as another factor of the template. These four categories of in-stream variables—habitat, hydrology, temperature, and chemistry—were also conceptualized as varying by ecological setting and thereby influencing biota assemblages by Cuffney et al. (2010), and were subsequently applied in the USGS National Water Quality Assessment of the impacts of urbanization on stream biota.

Habitat and geomorphology affect biotic responses to impervious cover, and may explain the variable fish and macroinvertebrate assemblages (Montgomery 1999). In streams with low levels of urbanization, channel geomorphology and riparian vegetation strongly influence other aspects of in-stream habitat, such as sediment storage, pool spacing, and presence and quantity of large wood (Segura and Booth 2010), which provide habitat for biota. Utz and Hilderbrand (2011) explored how geomorphic characteristics affected biotic response to urbanization. Benthic particle size, sediment movement, and sediment deposition were significantly different between the Coastal Plain and Piedmont physiographic regions in Maryland. Subsequently, urban streams in the Coastal Plain with finer, more mobile sediment had greater macroinvertebrate recolonization than urban sites in the Piedmont with larger, more stable bed materials. These findings led the authors to infer that low-gradient streams with fine bed materials were more resistant to urban-induced geomorphic change than steep-gradient streams with coarse materials (Utz and Hilderbrand 2011).

Geomorphology also interacts with hydrology to create flow conditions that differentially affect biota (Montgomery 1999). Hawley et al. (2016) demonstrated that streambed mobilization via flow exceedances (represented by Q_{critical}) was sufficient to degrade macroinvertebrate biotic integrity, despite high habitat and water quality conditions. Stream slope influences physical conditions within the stream channel (e.g., via bed mobility), as well as across the floodplain. Snyder et al. (2003) found that fish communities were more negatively affected by urbanization in streams with higher gradient compared to those urban streams in lower gradient catchments, potentially because high-gradient streams withstand more frequent flow disturbances, whereas lower gradient streams have more contact time with floodplains that potentially mitigate the effects of higher runoff.

Stream temperature, which is tightly linked to riparian forest cover, may also explain differences in biotic responses to urbanization (Caissie 2006). Poole and Berman (2001) suggested that physical characteristics of streams, such as stream order, channel morphology, and forestation, affect the relative sensitivity of streams to temperature changes from anthropogenic disturbances, with urbanization representing one such disturbance. In-stream thermal metrics vary across physiographic regions with different topography and geology: in urban streams in Maryland, thermal responses (e.g., mean and maximum temperature increases; duration of temperature surges) were more pronounced in the Piedmont, even though mean and maximum temperatures were higher overall in Coastal Plain streams (Utz et al. 2011). Although baseflow temperatures differed between urban and forested streams in North Carolina due to development and road density, differences in canopy closure and stream width also contributed to observed temperature differences (Somers et al. 2013). While forest cover across the watershed is important, it is particularly beneficial for stream quality when located along riparian corridors. An intact riparian zone has been shown to mitigate the effects of higher urbanization or impervious cover on macroinvertebrate communities (May et al. 1997, Miltner et al. 2004, Moore and Palmer 2005), perhaps because riparian vegetation plays a strong role in shaping channel geometry—regardless of the level of urbanization (Hession et al. 2003, Cianfrani et al. 2006)—as well as providing shade and inputs of leaf litter and wood (Cappiella et al. 2012). The beneficial role of riparian vegetation might be more important in watersheds with lower levels of urbanization (e.g., <15% urban land cover) than highly urbanized watersheds, at least for fish assemblages (Roy et al. 2007).

Lastly, water chemistry influences macroinvertebrates and fishes, and may explain differences in biotic responses to urbanization. Across metropolitan areas spanning climatic and physiographic regions, Bryant and Carlisle (2012) found that chemical parameters, including chloride, temperature, and hydrophobic organic contaminants, ranged several orders of magnitude within each metropolitan area.

Furthermore, the parameters that best explained biotic variability differed for each metropolitan area, indicating the potential importance of local characteristics to influence both physicochemical and biotic conditions.

Biotic responses to urban disturbance vary between taxonomic groups based on their life histories and sensitivities. Macroinvertebrates and fishes are two of the most commonly assessed taxonomic groups in monitoring programs (Barbour et al. 1999), and provide unique and complementary information about the status of the ecosystem. Each taxonomic group ranges in their diversity, morphology, mobility, behavior, life history (e.g., reproduction, generation time), and other traits (Resh 2008). For instance, macroinvertebrates are abundant, diverse, and have both terrestrial and aquatic life stages, despite relatively limited mobility within the stream channel; fishes have longer lifespans and can be highly mobile, but are confined to the stream network (Resh 2008). These differences can translate to different responses to urbanization (Carlisle et al. 2008, Walters et al. 2009), making it critical to use multiple taxonomic groups to best understand mechanisms of response to disturbance.

Biotic responses to urbanization also depend on the metrics used within each taxonomic group (i.e., macroinvertebrates or fishes), and may explain variation in responses at low levels of urbanization. Walsh et al. (2005) noted some inconsistencies in biotic responses to urbanization: while sensitive macroinvertebrates and sensitive fishes consistently decline and tolerant macroinvertebrates consistently increase, tolerant fishes do not respond consistently to increasing watershed urbanization. Assessments of stream condition have increasingly incorporated trait-based approaches, or a combination of taxonomic and functional measures to accurately represent the status of the system

(Heino et al. 2007). Traits and functional measures confer several advantages over taxonomic measures: they allow comparability across regions with different species pools (Verberk et al. 2013), provide a consistent framework to assess responses over different spatial scales (Viera et al. 2006), and reflect the adaptations of organisms to local environmental conditions (Richards et al.1997, Townsend et al. 1997a,b), independent of specific species' distributions influenced by climate, historical legacy, or dispersal (Hoeinghaus et al. 2007). Moreover, traits have been proposed as a metric to mechanistically link environmental stressors with biotic responses (Culp et al. 2011, Menezes et al. 2010). Ecological traits, including rheophily and thermal preference, are more evolutionarily labile than life-history traits (Poff et al. 2006b). Since traits that are more labile change based on environmental conditions, this serves as an advantage when used mechanistically in biological assessment. As such, flow and thermal traits were used to assess biotic condition in this study, in addition to the more commonly applied metrics of richness and tolerance.

This study examines which reach-scale factors explain variation in macroinvertebrate and fish assemblages when the total impervious cover is similar across catchments and whether responses vary among taxonomic groups and metrics. I focused on two low levels of impervious cover (1–4% and 7–10%), which are below reported thresholds of impervious cover (above which biota are consistently degraded; Booth and Jackson 1997, Horner et al. 1997, May et al. 1997, Wang et al. 2001, Walsh et al. 2007, King et al. 2011), yet may represent different conditions and biotic responses. Specifically, this study addresses the following research questions:

1. Which reach-scale predictors—representing habitat, flow, temperature, and water quality conditions—best explain biotic condition at sites with similar levels of impervious cover?
2. How do reach-scale predictors act in combination to explain biotic condition at sites with similar levels of impervious cover?
3. For both questions related to individual (1) and combinations of variables (2), how do the reach-scale predictors that best explain biotic condition differ by:
    a. Taxonomic group (macroinvertebrates or fishes)?
    b. Biotic response metric (richness, flow traits, thermal traits, tolerance)?
    c. Impervious band (very low 1–4%, low 7–10%)?

Results can help identify which physical and chemical characteristics of the system might act as constraints, thereby limiting or capping the attainment of higher-quality biotic condition, and conversely, which characteristics might act as buffers, allowing high biotic condition despite the stressors and disturbances imposed by increased impervious cover in the watershed.

2.2 Methods

2.2.1 Study area

This study was conducted at 40 stream sites across Massachusetts, in the northeastern United States. Massachusetts spans two main US EPA Level III ecoregions: the Northeastern Highlands in the western and north-central parts of the state, and the Northeastern Coastal Zone in the eastern part of the state (Hall et al. 2002, Griffith et al. 2009). Air temperatures are cooler and precipitation is slightly higher in the higher elevation Northeastern Highlands (7.3°C annual mean, 119 cm annual mean, 60–1014 m, respectively), compared to the Northeastern Coastal Zone (9.4°C annual mean, 117 cm annual mean, 0–364 m, respectively; Hall et al. 2002). Cape Cod and the Islands (Martha's Vineyard and Nantucket) in southeastern Massachusetts were not included in this study since simulated stream flows were not available for these areas at the time of study design, which led to their omission from other studies characterizing flow and fish communities in Massachusetts (Armstrong et al. 2011).

2.2.2 Site selection

The 40 stream sites were selected based on existing biotic data from the Massachusetts Department of Environmental Protection (MDEP) and Massachusetts Division of Fisheries and Wildlife (MDFW). Sites were screened from database containing samples from 823 macroinvertebrate sites and 5010 fish sites. For this study, sites had both macroinvertebrate and fish assemblage data collected within the past 11 years (2005–2015) from the same 200-m stream segment. Sites also met criteria for impervious level, agricultural use, and drainage area, described in the methods below.

The watersheds draining to each of the sampling sites were delineated in ArcGIS (Version 10.3, ESRI, Redlands, CA) with Massachusetts ArcHydro output. To reduce the influence of non-independence among sites, sites were selected from non-nested watersheds; sites with overlapping drainage areas were omitted. Watershed land cover and impervious cover were calculated using the 2011 National Land Cover Dataset (NLCD) land cover and impervious layers, respectively (Jin et al. 2013, Xian et al. 2011).

Twenty sites were selected within each of two narrow ranges of watershed impervious cover (hereafter referred to as bands): very low 1–4% (*n* = 20) and low 7–10% (*n* = 20) (Figure 2.1). Bands were chosen based on previously documented thresholds of biotic assemblage responses, such as 0.5–2% (macroinvertebrates, range attributed to physiographic region; King et al. 2011), 3.6% (fishes; Booth and Jackson 1997), and 4% (sensitive macroinvertebrates; Walsh et al. 2007) for the very-low band, and 8% (macroinvertebrates and fishes; Horner et al. 1997), 10% (May et al. 1997), 8–12% (range attributed to unconnected or connected impervious; Wang et al. 2001), and 12–15% watershed impervious cover (range attributed to fishes or macroinvertebrates; Klein 1979) for the low band. The threshold indicates a change point in the biotic condition, where the assemblage transitions from overall good condition to overall poor condition. Sites below the commonly cited 10% impervious threshold (Schueler et al. 2009) would therefore retain greater variability in biotic condition.

Sites also met criteria regarding watershed land use and drainage area to isolate the effects of reach-scale factors at sites with low impervious cover from other factors driving macroinvertebrate and fish assemblages. To minimize the confounding effects of agriculture, we only included watersheds with less than 20% agricultural land cover per the 2011 NLCD. Sites were restricted to small, wadeable streams with watersheds 5–80 km^2. The lower limit of 5 km^2 was used to develop the impervious cover model (Schueler et al. 2009); it also corresponds to the minimum drainage area used for calculation of stream flows at ungaged sites with the Sustainable Yield Estimator (SYE) tool (Archfield et al. 2010). The upper limit of 80 km^2 seeks to minimize potential outliers due to large drainage areas, while still being wadeable for sampling.

Seventeen sites met the site-selection criteria and had both macroinvertebrate and fish data collected in the same year; these sites were from the 2010–2014 MDEP probabilistic random sampling scheme. In cases where both macroinvertebrates and fishes were not collected by the same agency during the same year, sites were paired from each database. Closest facility analysis in ArcGIS 10.3 was used to match each MDEP macroinvertebrate site with the nearest MDFW fish site, based on the distance along National Hydrography Dataset streamlines. Sites located within 200-m on the same stream without confluences or road crossings between them were retained, which yielded an additional four sites. When sites met watershed criteria (i.e., impervious level, agricultural use, drainage area) but did not have both macroinvertebrate and fish samples, additional biotic sampling was conducted in 2014 and 2015 by MDFW and University of Massachusetts Amherst such that each study site had both macroinvertebrate and fish assemblage data. Ten sites were sampled for macroinvertebrates and ten sites were sampled for fishes. An additional two sites were sampled for both macroinvertebrates and fishes, since they met site-selection criteria but were not part of the existing databases.

2.2.3 Data collection

2.2.3.1 Reach delineation

Stream habitat and physicochemical data were collected at the 40 selected sites during 2014–2016. Stream sampling reaches were established based on the geographic positioning system (GPS) coordinates from biotic sampling conducted by MDEP and MDFW. Reach length was determined by estimating bankfull width on-site, then binning average bankfull width into reach length categories: 120-m reach for less than 6-m average bankfull width, 160-m reach for 6–8 m average bankfull width, and 200-m reach for greater than 8-m average bankfull width.

2.2.3.2 Longitudinal profiles and cross sections

I used longitudinal profiles to generate data for calculating stream slope, proportions of habitat areas, and transitions between habitat units. An electronic total station (Leica TS06 Plus ®, Leica Geosystems, Heerbrugg, Switzerland) was used to capture elevations for longitudinal profiles and cross sections based on similar survey protocols developed by Harrelson et al. (1994) and Bouwes et al. (2011). Three longitudinal profiles included water surface elevations at the left and right banks and thalweg. Water surface elevations were used to calculate local reach slope over stream channel length. The thalweg profile, in conjunction with left and right edges of water, was used to calculate habitat unit areas. The beginning and end of each habitat unit was marked along the thalweg (Lazorchak et al. 1998). Where one habitat unit ended and a different habitat unit began was classified as a habitat unit transition (Violin et al. 2011); the number of transitions was totaled for each reach. Habitat units of riffles, runs, and pools were distinguished in the field by considering a combination of water depth, velocity, turbulence, bed topography, water surface slope, and other hydrodynamically-influential factors, such as boulders and large wood (Frissell et al. 1986, Hawkins et al. 1993, Arend 1999). In order to standardize across sites of different stream sizes, the proportions of riffle, run, and pool habitat were calculated for each site. For the purpose of this study, only riffle and pool habitat were used in subsequent analyses, due to their importance as macroinvertebrate and fish habitat.

Bankfull characteristics and entrenchment were calculated from cross-sectional surveys. Elevations were also surveyed along five cross sections at each site, spaced equidistantly throughout the reach (i.e., 0, 25, 50, 75, 100% of reach length). Bankfull width, bankfull area, width-to-depth ratio, and entrenchment were calculated from the cross-section data with 3D Spatial Analyst in ArcGIS 10.3. Measurements from the five cross sections at each site were averaged and the coefficients of variation of each metric were calculated. A proxy measure of unit stream power was calculated using drainage area, discharge, slope, and bankfull width (Gartner et al. 2016).

2.2.3.3 Habitat assessment

Measurements of bed texture, sediment heterogeneity, and embeddedness were calculated from habitat surveys at transects. Twenty-one transects were established to subdivide each reach into 20 equidistant sections for sampling habitat variables. Streambed texture (i.e., substrate) was quantified using the toe method (Wolman 1954) in which five particles were sampled at 10, 30, 50, 70, and 90% of the wetted width along each transect within the main channel, as well as within any side channels if present (Heitke et al. 2011). The intermediate (‘B’) axis of each particle was measured. The bed texture measurements from each site were used to calculate a suite of particle size and distribution metrics, including D_{16}, D_{50}, D_{84}, heterogeneity, sorting, and gradation coefficient (Gordon et al. 2004, Laub et al. 2012). Sediment D_{16}, D_{50}, D_{84} refer to the 16th largest, 50th largest (median), and 84th largest particle in the rank-ordered particle distribution. Sediment heterogeneity, sorting, and gradation coefficient quantify different aspects of the particle spread and distribution, by using different calculations with D_{16},

D_{50}, and D_{84}. Along each transect, 5–10 coarse particles were visually inspected to estimate percent embeddedness, a measure of how much a coarse particle is surrounded by sand or finer sediments (Sylte and Fischenich 2002). Estimates at each transect were averaged for percent embeddedness at each site.

Stream banks were characterized based on two visual estimates: percent of the bank vegetated by perennial plants and roots; and percent of the bank with signs of erosion, indicated by the presence of crumbling banks, slumps, fractures, or exposed tree roots or soil (Bauer and Burton 1993). Presence of undercut banks was noted at each transect. Depositional features (i.e., lateral, mid, or point bars) were also recorded, with a visual estimate of areal percentage (Giddings et al. 2009). Visual estimates were aggregated to provide values of percent vegetated banks, percent eroded banks, percent undercut banks, and percent depositional features for each site.

Canopy cover was measured with a concave spherical densiometer, using a modified method such that vegetation is accounted for when it overlaps with the 17 visible intersections on the densiometer (Platts et al. 1987, Fitzpatrick et al. 1998, Lazorchak et al. 1998). Four canopy-cover measurements were taken from mid-channel at each transect: facing upstream and downstream, and towards the left and right banks (Lazorchak et al. 1998). Canopy-cover measurements at each transect were aggregated to calculate percent canopy cover for each site.

Riparian vegetation was sampled within 10 × 10 m plots on both banks of the stream channel at each of the five cross sections, for a total of 10 plots (0.1 ha total) at each site. Trees >3 cm diameter at breast height (DBH) were measured, from which basal area was calculated per site.

Large wood was quantified for the entire reach. Logs were tallied based on diameter and length classes (0.1–0.3, 0.3–0.6, 0.6–0.8, >0.8 m diameter; 1.5–5, 5–15, >15 m length) (Lazorchak et al. 1998). Wood was categorized as either within the bankfull channel or spanning above the bankfull channel (Lazorchak et al. 1998, Heitke et al. 2011). Wood volume was calculated based on the diameter and length classes (Kaufmann et al. 1999), and aggregated wood both within and spanning above the bankfull channel.

2.2.3.4 Temperature and water quality

Water temperature loggers (HOBO ® Pro v2 U22-001, Onset ®, Bourne, MA, USA) were deployed in the deepest section of each reach and recorded temperature at 15-min intervals. Initial deployment dates ranged from July 2014 to August 2015, with data downloaded from all sites in August 2016. Temperature logger data were used to calculate summer (June 1–August 30; or the available duration thereof) daily mean, maximum, minimum, and range, as well as maximum of summer daily means.

Water quality was sampled with a multi-probe meter (YSI Pro Plus ®, Yellow Springs, OH, USA) for dissolved oxygen, specific conductance, and nitrate. Water quality was measured seasonally in spring, summer, and fall, starting in summer 2014 through summer 2016; winter measurements were not taken due to safety considerations. Summary statistics (mean and coefficient of variation) were calculated for each water quality parameter across all sampling points. Since low dissolved oxygen, high specific conductance, and high nitrate are associated with water quality degradation, the minimum dissolved oxygen, maximum specific conductance, and maximum nitrate were calculated.

2.2.3.5 Macroinvertebrates

Macroinvertebrates were sampled with a rectangular-frame kick net in 10 riffles, which were aggregated into one sample for each site. At sites where no riffles were present, other habitats (e.g., submerged vegetation, leaf litter) were sampled in the proportions they were present. Samples collected from 2005–2011 were sorted, subsampled to 100 individuals, and identified by MDEP; samples from 2012–2015 were sorted, subsampled to 300 individuals, and identified by Cole Ecological, Inc. Macroinvertebrates were identified to the lowest feasible level, often genus or species.

Macroinvertebrate metrics were calculated for taxa richness, relative abundance of taxa with flow-adapted traits, relative abundance of taxa with coldwater thermal traits, and tolerance. Macroinvertebrate richness was rarefied to 100 individuals using the vegan package in R (Oksanen et al. 2016) to account for different subsample sizes (Gotelli and Colwell 2001). Flow-adapted traits were assessed using a combination of rheophily (erosional, erosional or depositional, depositional), shape (streamlined, not streamlined), swimming ability (none, weak, strong), and attachment (none, some, both) categories from the appendices in Poff et al. (2006b) and trait databases created by the U.S. Geological Survey (Vieira et al. 2006) and U.S. Environmental Protection Agency (US EPA 2012, 2016). Traits considered adapted to higher flows were: erosional rheophily, streamlined shape, strong swimming ability, and some attachment. Taxa with three of four flow-adapted traits were considered high-flow adapted, taxa with two traits were considered some-flow adapted, and taxa with one or no traits were considered low- or no-flow adapted (Appendix C.2). Since relatively few taxa were categorized as high-flow adapted based on trait aggregation, the relative abundance of macroinvertebrates with flow-adapted traits was considered as the aggregation of those species in the high- and some-flow adapted categories.

Thermal traits were also assessed using appendices from Poff et al. (2006b) and trait databases created by the U.S. Geological Survey (Vieira et al. 2006) and U.S. Environmental Protection Agency (US EPA 2012, 2016). The thermal categories used in these macroinvertebrate sources were cold stenothermal/cool eurythermal, cool/warm eurythermal, and warm eurythermal. Stenothermal refers to a narrow range of temperature tolerated by an organism, whereas eurythermal refers to a wide range of temperatures tolerated. The relative abundance of macroinvertebrate taxa in the cold stenothermal/cool eurythermal category was used as the thermal trait metric.

Each macroinvertebrate taxon in the MDEP database was assigned a tolerance score from 0–10, with 0 representing the least tolerant and 10 the most tolerant. A tolerance index score for the macroinvertebrate assemblage at each site was calculated according to the methods established by Hilsenhoff (1998).

2.2.3.6 Fishes

Fishes were sampled by MDFW, MDEP, and University of Massachusetts Amherst using single-pass electrofishing with one or two backpacks (Smith-Root LR-20B Electrofisher ®, Vancouver, WA, USA), depending on stream size. Dip nets were used to capture shocked fish. Electrofishing occurred over a minimum 100-m sampling reach, with reach lengths for larger streams (target length = 20 times wetted width). Fishes were identified to species level, enumerated, and then released.

Fish metrics were calculated for species richness, relative abundance of fluvial species, relative abundance of coldwater species, and relative abundance of intolerant species. Fish species were classified as fluvial specialists if they require lotic habitat throughout their life cycle; fluvial dependents if they require lotic habitat during part of their life cycle (e.g., for spawning); or macrohabitat generalist if their life cycle can be completed in either lotic or lentic habitats (Armstrong et al. 2011). For this study, fluvial dependents and fluvial specialists were combined into one category of fluvial fishes, for which the relative abundance was calculated. Coldwater and intolerant species were determined based on MDFW classifications for thermal preference (coldwater, coolwater, warmwater) and tolerance level (intolerant, intermediate, tolerant). Flow, thermal, and tolerance classifications for each fish species can be found in Appendix C.3.

Macroinvertebrate and fish response metrics for richness, flow traits, thermal traits, and tolerance were compared both with scatterplots and spider plots. Scatterplots compared biotic responses in relation to impervious cover, with each response metric displayed individually. Spider plots allow multiple metrics at the same site to be visualized and compared simultaneously. The “web” is scaled such that the center represented the lowest value across sites and the outer edge represents the highest value across sites. Each “spoke” of the web has a point for the value of the response metric; eight spokes for eight response metrics. When the points are connected on the web, the resultant shape can then be compared to other sites with similar or divergent condition based on multiple metrics. Spider plots were generated in R with the fmsb package (Nakazawa 2015).

2.2.4 Statistical analyses

Generalized linear models (GLMs) with a model section approach were used to evaluate the relative influence of reach-scale factors for explaining variance in macroinvertebrate and fish assemblage metrics within very-low (1–4%) and low (7–10%) bands of impervious cover. Several steps were used to select the model type, impervious cover variable, and predictor variables used in the final models, as described below.

Generalized linear models were developed for each biotic response metric (Table 2.1; Zuur et al. 2012) using the stats package in R (R Core Team 2016). GLM distributions were chosen based on the characteristics of the response metric: macroinvertebrate richness and macroinvertebrate tolerance used a Gaussian (i.e., normal) distribution; fish richness used a Poisson distribution appropriate for zero-bounded count data; and relative abundances of macroinvertebrate and fish flow traits, coldwater macroinvertebrates and fishes, and intolerant fishes used a binomial distribution with logit link function appropriate for proportional data. The Shapiro-Wilk test was used to assess normality in the distributions of response variables. Macroinvertebrate richness and macroinvertebrate tolerance were normally distributed; the other response variables had non-normal distributions. Log transformations did not improve normality of the remaining response variables and thus were not used. Binomial GLMs had extreme overdispersion (ratio of residual deviance to degrees of freedom, for which a value greater than 1 indicates overdispersion; Warton and Hui 2011); thus, generalized linear mixed models (GLMMs) with a random effect for sampling site were run for all proportional response variables using the lme4 package in R (Bates et al. 2015).

To appropriately account for impervious cover in models explaining biotic assemblages, four different measures of impervious cover were tested for use in subsequent analyses. The four measures differed based on the source (NLCD or MassGIS), which varied based on year (2011 or 2005, respectively) and resolution (30-m or 1-m, respectively), and whether it was represented as a continuous or categorical (i.e., by band) variable. The four impervious cover measures were: (1) NLCD 2011 impervious cover as a continuous variable (30-m resolution with each pixel assigned a value of 0–100% impervious); (2) NLCD 2011 impervious cover binned as a categorical variable as belonging to either the very-low (1–4%) or low (7–10%) band; (3) an interaction between NLCD 2011 continuous value (1) and categorical band (2), since the slopes of the regression lines were presumed to differ for each band; and (4) MassGIS 2005 impervious cover (1-m resolution with each pixel assigned a 0 or 1 for absence or presence of impervious cover, respectively) as a continuous variable. Four models were developed for each biotic response metric (n = 40), one for each of the aforementioned conditions (1)–(4). Models that included NLCD 2011 impervious cover as a continuous variable usually had lower Akaike Information Criterion (AICc) values; therefore, NLCD 2011 as a continuous variable was used to represent impervious cover in all subsequent models that included reach-scale factors.

Predictor variables were organized into four categories of non-redundant variables representing habitat, flow, temperature, and water quality conditions (hereafter ‘predictor categories’), with hypothesized power for explaining biotic variation independent of impervious cover. Collinearity was evaluated using Spearman rank correlations between pairs of variables within each category (Appendix G). If variables were highly collinear ($r \geq |0.7|$), one variable was retained for further analyses.

In order to select the variable that best represented each predictor category, I created a candidate set of alternative models to evaluate the relative importance of reach-scale factors for each biotic response metric. All alternative GLMs included two predictor variables: impervious cover (NLCD 2011 as a continuous variable) and one reach-scale predictor variable representing habitat, flow, temperature, or water quality conditions. GLMMs also contained a random effect on site. In order to account for variables collected on different scales (i.e., ranging different values), z-score standardization (mean = 0, standard deviation = 1) was applied to predictor variables using the biostats package in R (McGarigal *unpublished*). Model selection with Akaike Information Criterion (AIC), corrected for small sample size (AICc; Burnham et al. 2011) was used to compare alterative models within the candidate set. Models with lower AICc values represent more plausible models compared to other models in the candidate set. For the model with the lowest AICc within each predictor category, the variance explained was calculated, including the additional variance explained compared to models with impervious as the single predictor.

Finally, I determined how combinations of variables might better explain biotic condition than individual predictors. The predictor variable that occurred in the best-supported model (lowest AICc value) within each predictor category was retained for use in global GLMs and GLMMs for each biotic response metric. All subsets of GLMs and GLMMs were run with every combination of impervious cover and the four variables selected from each predictor category, for a total of 31 models. Models within 2 AICc values of the most plausible model are considered similarly plausible. Akaike weights (*w*) were calculated based on the relative likelihood values, to assess the weight of evidence for the best-supported model (Burnham et al. 2011). Variable importance was calculated for each variable included in equally plausible models, by summing the model weight for each model in which that variable occurred. Variable importance was used to assess the relative importance of impervious cover, habitat, flow, temperature, or water quality predictors for explaining biotic condition.

2.3 Results

2.3.1 Site characteristics

For the 40 sites that were included in this study, the 20 sites in the very-low impervious band ranged from 1.1–3.7% watershed impervious cover, whereas the 20 sites in the low band ranged from 6.7–10.0% watershed impervious cover, according to the 2011 NLCD. The low band included one site that was <7% total impervious area due to a miscalculation during site selection. Drainage areas ranged from 5.8–72.1 km^2 in the very-low band and 5.3–66.3 km^2 in the low band. Agriculture ranged from 0.3–15.8% of total land cover in the very-low band and 0.0–20.4% in the low band.

2.3.2 Biotic responses

Across the 40 sites, 318 macroinvertebrate taxa were sampled (Appendix B.1). The most cosmopolitan macroinvertebrate taxa were the caddisfly larvae *Cheumatopsyche* sp., which occurred at 34 of 40 sites, black fly larvae *Simulium* sp. at 29 sites, and caddisfly larvae *Hydropsyche betteni* at 26 sites. Thirty-eight taxa occurred at

>10 (25%) sites, 119 taxa occurred at >4 (10%) sites, and 113 taxa were only sampled at one site. Two macroinvertebrate taxa (0.6%) were not classified for flow traits and 46 taxa (14.5%) were not classified for thermal traits due to lack of information in existing trait databases. Of the remaining macroinvertebrate taxa, 115 taxa (36.2%) were classified as having flow-adapted traits and 88 taxa (27.7%) were coldwater. Macroinvertebrate tolerance indices for the aggregate assemblage at each site ranged from 3.4–7.7, based on a scale ranging from intolerant (0) to tolerant (10).

Thirty fish species were sampled across the 40 sites (Appendix B.2). The most cosmopolitan species were white sucker (*Catostomus commersoni*) at 26 sites, pumpkinseed (*Lepomis gibbosus*) at 19 sites, and blacknose dace (*Rhinichthys atratulus*) and fallfish (*Semotilus corporalis*), each at 15 sites. Twelve of the 30 total species were considered fluvial (fluvial dependent or fluvial specialist), four species were coldwater, and five species were intolerant (Figure 2.2). Three fish species—slimy sculpin (*Cottus cognatus*), brown trout (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*), which occurred at one, four, and 13 sites, respectively—overlapped in all three classifications of fluvial, coldwater, and intolerant fishes.

Macroinvertebrate and fish responses were highly variable within each band of impervious cover (Figure 2.3), as predicted by the impervious cover model (Schueler et al. 2009). However, all response metrics—except macroinvertebrate tolerance for which the index was scaled from intolerant to tolerant—had greater variation within the low band than the very-low band. Across each response group of richness, flow traits, thermal traits, and tolerance, fish response values were more dispersed than macroinvertebrate responses, as indicated by higher coefficients of variation.

Several patterns emerged from the macroinvertebrate and fish responses, as demonstrated by spider plots for selected sites (Figure 2.4; see Appendix E for spider plots from all 40 sites). Taxonomic groups did not necessarily respond similarly, even within the same site. For example, at East Branch Housatonic River (Figure 2.4A), flow trait occurrence was low for macroinvertebrates yet high for fishes; coldwater trait occurrence was high for macroinvertebrates yet low for fishes; and macroinvertebrates overall comprised an intolerant assemblage while there were few intolerant fishes. Within taxonomic groups, response variables were not necessarily concordant. At the Kinderhook River (Figure 2.4B), although fish richness was about average across sites within this study, the relative abundances of fluvial fishes, coldwater fishes, and intolerant fishes were very high compared to other sites in this study. Since biotic condition demonstrated considerable scatter (Figure 2.3), some sites with low impervious cover had overall poor biotic condition, whereas other sites with relatively high impervious cover had overall good biotic condition. Fall Brook (Figure 2.4C), with 2.6% watershed impervious cover, had low macroinvertebrate and fish richness, few macroinvertebrates and fishes with fluvial or coldwater traits, an overall tolerant macroinvertebrate assemblage, and few intolerant fishes. On the other hand, the Westminster site (Figure 2.4D) had 10.0% watershed impervious cover, yet hosted many fluvial fishes, many coldwater macroinvertebrates, and an overall intolerant macroinvertebrate assemblage.

2.3.3 Reach-scale predictors

Habitat metrics covered aspects of channel geometry, habitat units, sediment, stream banks, and large wood. Mean bankfull width, riffle habitat, and three sediment measures (D_{50}, D_{84}, and gradation coefficient) were eliminated due to collinearity with other bankfull, habitat, and sediment measures, respectively, leaving 14 candidate variables. Mean bankfull area had a wider range within the very-low band to the low band, but coefficients of variation in bankfull area and width were similar across bands (Table 2.2). Sites in the very-low band had higher average pool habitat and more transitions between habitat units compared to sites in the low band: 18.8% and 14.8% pool habitat and 6.7 and 6.1 transitions, respectively. Sediment D_{16} was smaller on average in the low band, with more sediment heterogeneity and sediment sorting in the very-low band. Although average embeddedness was higher on average in the low band, there was a wider range within the very-low band. Stream banks tended to be less vegetated, less eroded, and more undercut in the very-low band compared to the low band. Although there were sites in both bands that did not have any large wood present, very-low-band sites overall had much higher volumes of large wood than low-band sites (Table 2.2).

Flow conditions were characterized by proxy measures of channel geometry and stream power. Slope and stream power were highly correlated ($r = 0.95$), and thus, stream power, which integrates aspects of drainage area, discharge, slope, and bankfull width, was retained as a proxy for flow conditions in the absence of direct measurements at each site. Channel dimensions of width:depth ratio (mean, coefficient of variation [cv]) and entrenchment (mean, cv) did not differ by band (Table 2.2). Stream power differed considerably by band: sites in the very-low band had a much higher average and wider range of stream power than sites in the low band (Table 2.2).

Temperature was represented by two proxy measures—canopy cover and riparian vegetation—and five direct measures of water temperature derived from in-stream temperature loggers: mean summer daily mean, maximum summer daily mean, mean summery daily minimum, mean summer daily maximum, and mean summer daily range. Since the in-stream temperature metrics, except daily range, were highly collinear with one another ($r \geq 0.82$), only mean summer daily maximum and mean summer daily range were retained in subsequent analyses. Canopy cover and riparian vegetation generally exhibited the same patterns between bands, although the very-low band had a higher minimum canopy cover (Table 2.2). Water temperatures were on average warmer in low-band sites (22.3°C) than very-low-band sites (20.7°C), with greater mean diel fluctuation (3.1°C and 2.8°C, respectively).

Dissolved oxygen mean and coefficient of variation were similar across bands, as was specific conductance coefficient of variation (Table 2.2). In contrast, mean specific conductance (i.e., averaged across each seasonal sampling visit) was much higher in the low band: conductance ranged from 59.5–590.5 µs/cm in the very-low band and 205.1–974.5 µs/cm in the low band, with means of 224.0 and 387.5 µs/cm, respectively. Mean nitrate exhibited the opposite pattern, with wider range and higher mean in the very-low band (range 0.2–27.2 mg/L; mean 6.3 mg/L) compared to the low band (range 0.8–14.0 mg/L; mean 3.7 mg/L) (Table 2.2). Minimum dissolved oxygen, maximum specific conductance, and maximum and coefficient of variation nitrate were eliminated due to high collinearities with other water quality variables.

2.3.4 Predictor-response relationships

The best-supported variables (i.e., ΔAICc = 0) within each predictor category of habitat, flow, temperature, and water quality differed across taxonomic groups, biotic response metrics, and by impervious band (Table 2.3, Figure 2.6, Appendix H). In general, water temperature predictors, particularly mean summer daily maximum temperature, tended to explain the most additional biotic variance after accounting for impervious cover. Habitat (most often represented by aspects of bed texture) and water quality (e.g., nitrate, dissolved oxygen) also explained a substantial amount of variance for some of the biotic metrics and impervious bands. In contrast, flow-related variables did not explain much variance. Combinations of predictor variables determined through all-subsets modeling and variable importance similarly showed differences across taxa, metric, and band (Table 2.4, Figure 2.7, Appendix I).

2.3.4.1 Taxonomic group

Between the two taxonomic groups, reach-scale variables tended to explain more variance in fish assemblages than macroinvertebrate assemblages (Table 2.3). Habitat and temperature predictors added more explanation of variance for fish assemblages, whereas habitat and water quality predictors explained more variance in macroinvertebrate assemblages. Habitat measures were most often represented by characteristics of the channel substrate (e.g., sediment D_{16}, embeddedness, sediment heterogeneity, depositional features), as well as large wood, and sometimes by channel dimensions (e.g., bankfull area or bankfull width). Mean nitrate commonly occurred as the water quality predictor that added more explanation of variance for macroinvertebrate assemblages. For fishes, a wider variety of predictors explained more variance, including temperature (e.g., mean summer daily maximum), habitat (e.g., large wood, bank vegetation), and sometimes flow measures (e.g., entrenchment). Variable importance from all-subsets (Table 2.4) showed similar patterns: habitat and water quality were most important for macroinvertebrates, while habitat and temperature were more important for fishes. Impervious cover was a more important variable in macroinvertebrate models than fish models.

2.3.4.2 Biotic response metric

Individual predictors and the amount of additional variance they explained differed considerably across the four types of biotic response metrics (Table 2.3). For macroinvertebrates, reach-scale predictors explained the most variance for richness and tolerance. None of the tested reach-scale predictors explained much variance for either macroinvertebrate flow traits or coldwater thermal traits: conditional-R^2 was <0.10 for most models, with the exception of habitat and temperature predictors in the high band. Fish metrics were less differentiated: reach-scale predictors explained similar amount of variance across richness, flow traits, and coldwater traits. For intolerant fishes, however, temperature (represented by mean summer daily maximum) had conditional-R^2 much higher than habitat, flow, or water quality predictors, regardless of the band tested: additional $R^2 = 0.41$ for very-low band, additional $R^2 = 0.62$ for low band in addition to the variance explained by total impervious cover. The total variance explained when multiple variables were used with all-subsets modeling also tended to be higher for fish assemblages than macroinvertebrates, across all metrics except tolerance (Appendix I).

2.3.4.3 Impervious band

Reach-scale predictors tended to explain more variance for biotic responses in the low band compared to the very-low band (Table 2.3). Impervious cover also contributed greater variance explained in the low band, particularly for macroinvertebrate richness and tolerance, and fish richness and coldwater relative abundance. In contrast, impervious cover explained more variance for both tolerance metrics in the very-low band, but was relatively minor compared to the variance explained by selected reach-scale predictors for other very-low band response metrics. The predictors that explained the most additional variance were similar across bands, except for richness. In the very-low band, macroinvertebrate richness was best explained by water quality (mean nitrate; additional $R^2 = 0.25$) and temperature (canopy cover; additional $R^2 = 0.17$), but in the low band, was best explained by habitat (sediment D_{16}; additional $R^2 = 0.35$) and temperature (mean summer daily maximum; additional $R^2 = 0.22$). When the very-low and low band were analyzed separately, flow predictors were ranked as more important variables, and total impervious was less important than when both bands were analyzed together (Table 2.4).

2.4 Discussion

2.4.1 Reach-scale variables explain differences in biotic condition

Habitat measures, particularly sediment (i.e., heterogeneity, embeddedness) and large wood, were the most important variables for coldwater fishes and macroinvertebrate tolerance. While several studies documented higher macroinvertebrate diversity with higher substrate complexity and roughness, substrate heterogeneity, median particle size, substrate type or area, habitat type, and shading, other studies did not find any effect of the same or similar metrics on diversity (Vinson and Hawkins 1998). In this study, habitat metrics did not strongly explain variation in richness, although higher percentage of vegetated banks were related to higher fish richness in the very-low band. Vinson and Hawkins (1998) added the caveat that some of the inconsistency in relationships between biotic diversity and habitat heterogeneity might be attributable to how heterogeneity is measured, and the range of conditions quantified for each variable. Since means can obscure important differences between sites (Palmer et al. 1997, Fraterrigo and Rusak 2008), the coefficients of variation were used in addition to means as predictors for channel geometry and water quality variables. Although means were represented in the top models more often than coefficients of variation for the same variable (e.g., mean and coefficient of variation calculated for width:depth ratio from five cross sections), in a few cases (e.g., bankfull area) the coefficients of variation predictors performed better than mean predictors. In addition, several measures of streambed particle distribution and dispersion were used to represent habitat diversity. Of the three measures of sediment dispersion, only sediment heterogeneity was found in top models; sediment sorting and gradation coefficient did not perform well in comparison. Although sediment dispersion predictors did explain much additional variance, other aspects of bed texture (e.g., sediment D_{16}, embeddedness, depositional features) were often ranked as important variables, potentially indicating the role of fine sediment and sedimentation in low-level urban streams.

The suite of predictors developed to quantify flow conditions did not explain macroinvertebrate or fish flow traits better than variables in the other predictor categories of habitat, temperature, or water quality. Flow variables were not important across most biotic response metrics, not just for fluvial traits. While flow variables rarely explained the most additional variance, when used in combination with other habitat, temperature, or water quality variables, sometimes were ranked as important (Table 2.4). Since only five flow predictors were tested, they appeared with relatively similar frequently for variable importance. The flow predictors used in this study were proxies, in the absence of discharge data to directly quantify flow conditions. Slope and stream power were highly correlated for sites in this study ($r = 0.95$). Although slope is often an important predictor of biotic assemblages (regardless of urbanization or anthropogenic degradation), stream power did not emerge as a strong predictor of additional variance or importance. Where stream power did occur, it often explained <0.25 additional variance; the strongest was in explaining coldwater fishes.

Although the suite of temperature predictors tested did not better explain thermal traits for either assemblage, it was overall one of the most important predictors for reach-scale variables. Temperature predictors attempted to both directly (via water temperature measurement) and indirectly (via vegetative shading) explain thermal traits, but were outperformed by habitat and flow predictors for coldwater response metrics. Although water temperature has been linked more strongly to local influences such as canopy cover than watershed influences such as total development (Hester and Doyle 2011, Booth et al. 2014), canopy cover and riparian vegetation were not strongly correlated with any of the water temperature metrics calculated in this study ($r < 0.30$). Temperature predictors, particularly average summer daily maximum temperature, were important more often for fish metrics (especially intolerant fishes) than macroinvertebrates. Hester and Doyle (2011) found that not only are fishes are more sensitive to temperature change than macroinvertebrates, but organisms are more sensitive above their thermal maxima, a finding that appears to be corroborated by this study.

Higher mean nitrate and higher mean dissolved oxygen were particularly important for explaining higher macroinvertebrate richness and more fluvial fishes, respectively. While the latter finding is expected—that fluvial fishes live in well-oxygenated waters, such as riffle habitat—the former finding is counter to that expected. However, since greater macroinvertebrate richness exists with higher macroinvertebrate tolerance, greater eutrophication (as indicated by higher nitrate) could elevate richness while still degrading overall stream quality. Specific conductance usually did not explain the most additional variance, but was an important variable for macroinvertebrate richness, tolerance, and coldwater taxa. Specific conductance was often more important in the low band compared to the very-low band, which might be attributed to the higher maxima and coefficients of variation in this predictor for sites in the low band. While in-stream habitat, represented by sediment D_{16}, was the most important variable in low-band macroinvertebrate richness models, mean nitrate was the most important variable in very-low band models. Although Roy et al. (2003) also found that water quality parameters were important predictors of macroinvertebrate richness, this pertained to lower specific conductance with higher richness.

2.4.2 Fish and macroinvertebrate responses differ

Overall, fish assemblages were better explained by reach-scale variables than macroinvertebrate assemblages. Several studies in urbanizing streams also found that fish assemblages were strongly correlated with reach-scale metrics. For instance, Wang et al. (2003) found strong evidence for water temperature and baseflow as important predictors of fish assemblage metrics (i.e., richness, biotic integrity, coldwater fishes, intolerant fishes) at low levels of impervious cover.

Few studies of urban streams have investigated both biotic assemblages concurrently in order to sufficiently compare assemblage responses. The USGS NAWQA study is one exception, in that it compared multiple biotic assemblages (algae, macroinvertebrates, fishes) in relation to numerous physicochemical and landscape parameters, across multiple metropolitan areas nationwide (Cuffney et al. 2010). Results from the NAWQA assessments in urban streams found macroinvertebrates were better related with urban metrics than fishes. Bryant and Carlisle (2012) found that macroinvertebrates were more strongly related to physicochemical factors in urban streams than fish assemblages, though the specific physiochemical parameters varied in importance by metropolitan area. Walters et al. (2009) investigated a broader suite of land cover, geomorphological, and water quality variables to compare both macroinvertebrates and fishes in urbanizing streams. As with this study, Walters et al. (2009) found that macroinvertebrates and fishes were explained by different variables. Of the reach-scale variables investigated, conductivity, fine sediment, and local topological relief were better predictors for macroinvertebrates, while embeddedness, turbidity, and slope were better predictors for fishes. Compared to this study, measures of bed texture were also important for macroinvertebrate assemblages, while less important for fishes, and nitrate was a more important variable than specific conductance.

2.4.3 Responses vary based on the biotic metric used

The assessment of condition at each site differed based on the specific choice of biotic response metric. For instance, if macroinvertebrate or fish richness were the sole or principal response variable, then the Kinderhook River site (Figure 2.4B) would be considered average condition relative to other sites in this study. However, the Kinderhook River site had high relative abundance of fluvial fishes, coldwater fishes, and intolerant fishes, indicating that the site had high biotic integrity—at least, for fishes—as it had one of the highest levels of integrity across all study sites. This case indicates one of the issues with using richness as a measure of biotic integrity. High-gradient coldwater sites have a more limited species pool in Massachusetts, while lower gradient warmwater sites tend to have more diverse fish assemblages (Kashiwagi and Richards 2009). Invasive species can also contribute to higher species richness (Meador et al. 2005), although such species are often considered detrimental to the biotic community and ecosystem functioning. In streams subjected to increasing urbanization, Helms et al. (2005) observed that while fish health, biotic integrity, and sensitive breeding guilds declined, fish richness and diversity did not, nor did tolerant species become more prevalent.

The lack of differentiation among flow, thermal, and tolerance response metrics for fish assemblages in this study might be attributable to the overlap in species classifications (Figure 2.2). Of the 30 fish species collected across the 40 sampling sites, 13 species were included in analyses due to their classification as fluvial, coldwater, and/or intolerant, while a greater diversity of fishes—representing 17 species—were omitted from trait and tolerance metrics (Figure 2.2). No fish species were strictly coldwater without also being fluvial and/or intolerant; only one species (swamp darter; *Etheostoma fusiforme*) was intolerant without also being fluvial and/or coldwater.

Although classification of fish species into categories of cold, cool, and warmwater thermal regimes is common in fisheries management (Magnuson et al. 1979, Lyons et al. 1996, Beauchene et al. 2014), it is also fraught with complications (Wehrly et al. 2003). Classification into discrete thermal categories does not allow for plasticity in fish traits (Frimpong and Angermeier 2010), nor do classes use consistent temperature ranges to quantify categories across regions (Lyons et al. 2009, Beauchene et al. 2014). Furthermore, current and historical ecological degradation affects the ability to accurately delineate thermal regimes (Kanno et al. 2010). Additional information about whether fish species are stenothermal or eurythermal—tolerant of a narrow or wide range of temperatures, respectively—would aid in interpretation of fish response to thermal gradients and thermal stress. Wehrly et al. (2003) suggested three categories of extreme, moderate, and stable temperature fluctuation in additional to traditional cold, cool, and warm mean temperature classes; this finer accounting for regional variability in stream temperature contributed to more accurate assessments of fish biotic integrity in Michigan streams. Beauchene et al. (2014) used indicator species analysis for fish species in Connecticut to determine specific temperature ranges for coldwater and warmwater classes, with a coolwater transitional class between the two. Massachusetts and Connecticut share many of the same ecoregions (Griffith et al. 2009) and fish species pools, which allow comparability between assessments across the two southern New England states. Several important differences emerged between Beauchene et al. (2014) and this study: while Beauchene et al. (2014) classified six fish species as indicative of cold-cool or cool-warm transitional communities, this study used distinct categories of cold, cool, or warmwater. Brown trout (*Salmo trutta*) was indicative of cold-cool transitional in Connecticut, but coldwater in Massachusetts; this difference likely did not influence analyses in this study. However, fallfish (*Semotilus corporalis*) was classified as coldwater in Massachusetts (likely due to an error in classification; T. Richards, *pers. comm.*) but classified as coolwater according to Kanno and Vokoun (2010) and indicative of cool-warm transitional communities by Beauchene et al. (2014) in Connecticut. This constitutes an important distinction that likely affected analyses of coldwater fish assemblages in this study, particularly since fallfish often occur in large numbers that can skew relative abundances at certain sites (T. Richards, *pers. comm.*). Across the 40 sites in this study, fallfish were sampled at 15 sites. Fallfish were the only fish classified as coldwater at 9 of these 15 sites, while at an additional 4 sites fallfish comprised > 50% relative abundance of coldwater taxa. The other species classified as coldwater in Massachusetts are brown trout, brook trout, and slimy sculpin (Figure 2.2, Appendix C.3). Slimy sculpin, commonly an indicator of cold, flowing waters, was only sampled at one site, the Kinderhook River, and comprised 65.5% relative abundance of the coldwater assemblage at that site. Had the coldwater assemblage been reassessed based on differences in classification (in the case of fallfish) and sufficiency (in the case of slimy sculpin), the coldwater assemblage would be comprised of brown trout and brook trout, with the latter being the predominant species in terms of cosmopolitan distribution across sites and relative abundance within those sites. The coldwater and intolerant fish response metrics would therefore likely be explained by similar suites of predictor variables, given that each assemblage composition would be dominated by brook trout.

Choice of metric is also relevant for an accurate assessment of condition in terms of macroinvertebrate assemblages. As with fish assemblages, higher richness does not necessarily indicate a higher-quality macroinvertebrate assemblage. Of the macroinvertebrate taxa collected across the sites in this study, the majority of taxa—based on either taxa richness or relative abundance—are classified with an intermediate tolerance value (e.g., 4–6, on a scale of 0–10; Figure 2.5). Relatively few macroinvertebrate taxa were classified as intolerant (e.g., score of 0–3). Of the metrics used to quantify macroinvertebrate assemblages, the tolerance index was overall better explained by reach-scale factors than other response metrics. The tolerance index (based on Hilsenhoff et al. 1998) is well established and commonly used in assessment and monitoring programs (Barbour et al. 1999). Furthermore, the tolerance index for a site represents an aggregate score derived from the relative abundances of all taxa observed at a site. Meador and Carlisle (2007) found that the differences between tolerant and intolerant fish classifications were driven more by differences in suspended sediment, specific conductance, chloride, and total phosphorus.

By contrast, macroinvertebrate fluvial traits had very low variance explained by reach-scale factors or impervious, either individually or in combination (conditional-R^2 <0.10). Several studies have demonstrated empirical relationships between flow conditions and macroinvertebrate traits: Townsend et al. (1997b) found higher relative abundances of taxa with high adult mobility and streamlined/flattened shape with more disturbances related to streambed movement (albeit not discharge variation); Lamouroux et al. (2004) found that invertebrates that were small, streamlined, and with shorter lifespans were more common in reaches with higher stream stress and Froude number; Dolédec et al. (2006) and Carlisle and Hawkins (2008) found streamlined shape and attachment were related with flow disturbance or channel instability; and Horrigan and Baird (2008) suggested low crawling rate, common in drift, short lifespan, erosional rheophily, and medium size as potential flow-indicator traits based on observed relationships of macroinvertebrate assemblages with flow fluctuations. While this study incorporated physiological traits of shape, swimming ability, and attachment, perhaps physiological traits representing reproduction, life span, life history, and drift would have been better explained by reach-scale factors, particularly those related to flow.

In contrast to physiological traits, ecological traits such as rheophily or thermal preference are ultimately more applicable to biological assessments, due to their plasticity to change with changing environmental conditions (Poff et al. 2006b, Vieira et al. 2006). In this study, the flow-trait aggregation metric included rheophily as one of the traits, but further work might be better suited to utilize rheophily individually, not in aggregation with physiological traits. Another option would be to assess macroinvertebrates via a metric of EPT (Ephemeroptera, Plecoptera, Trichoptera) taxa richness or relative abundance. EPT is commonly used in ecological assessments (Barbour et al. 1999) and shows more consistent declines along gradients of urbanization (Roy et al. 2003, Wang and Kanehl 2003, Coles et al. 2010). Indeed, for the sites in this study, erosional rheophily was strongly correlated with relative abundance EPT (r = 0.96; data not shown), indicating that not only is EPT a good measure of macroinvertebrate sensitivity overall, but of fluvial conditions specifically.

Macroinvertebrate thermal traits were also poorly explained by impervious and reach-scale factors. This study used a direct ecological measure of thermal preference (i.e., cold stenothermal/cool eurythermal, cool/warm eurythermal, and warm eurythermal), rather than a suite of physiological traits to assess change along a thermal gradient. One issue with the use of thermal traits for this study is that 46 taxa (14.5%) were not classified for thermal traits due to lack of information in existing trait databases. These unclassified taxa comprised 0.0–41.0% of the assemblage across the 40 sites; the majority of sites had <10% unclassified taxa, but 7 sites had 10.0–41.0% unclassified taxa by relative abundance. Furthermore, the thermal trait data were sourced from nationwide databases (Poff et al. 2006b, Vieira et al. 2006, US EPA 2012, 2016), not necessarily Northeast regional or Massachusetts-specific thermal classifications. Although data on macroinvertebrate thermal tolerances are limited, increased data availability might increase the power of reach-scale variable to explain this metric. Alternately, a measure such as EPT can be applied. As with flow traits, EPT taxa comprise a relatively intolerant assemblage that prefers cold, flowing water with high oxygen and low sedimentation. EPT could be used as a surrogate for coldwater taxa, as they could also be effectively employed to measure flow conditions.

Although there is much ecological theory underpinning the use of macroinvertebrate traits for diagnostic assessments (Townsend and Hildrew 1994, Townsend et al. 1997a,b), the practical applicability for mechanistic determination of stressors (Menezes et al. 2010, Statzner and Bêche 2010, Culp et al. 2011, Verberk et al.

2013), particularly in urban streams with myriad stressors, falls short in empirical studies (e.g., Zuellig and Schmidt 2012), including this one. Rather than expanding trait analyses for which there are limited data, we suggest using existing data for well-established metrics, such as EPT richness or relative abundance, that are correlated with high-quality stream condition.

2.4.4 Reponses vary based on impervious cover band

The predictor variables that were most important, as well as the amount of variance explained, in biotic response models differed based on very-low or low impervious band. The most important variables in the low band (Table 2.4) were often aspects of channel geometry (classified as either habitat or flow predictors), including entrenchment, bankfull area, width:depth ratio. By contrast, the most important variables in the very-low band often related to habitat (vegetated banks, large wood, embeddedness) and temperature. Impervious also appeared as a more highly ranked important variable in the low band. This could indicate that the effects of urbanization are already manifesting, such as by changing channel width, depth, and shape (Booth and Henshaw 2001).

2.4.5 Conclusion

Reach-scale factors, representing habitat, flow, temperature, and water quality conditions, explained additional variance in macroinvertebrate and fish assemblages in streams with similar levels of low impervious cover. Colder water temperatures, higher dissolved oxygen, and more large wood were related to higher proportions of fluvial, coldwater, and intolerant fishes. For macroinvertebrates, warmer water temperature, smaller sediment size, and higher nitrate were related to higher macroinvertebrate richness and tolerance. Based on the reach-scale variables that contributed to higher biotic integrity, efforts should be taken to minimize impacts that would degrade these conditions.

Table 2.1. Specifications for generalized linear models (GLMs) and generalized linear mixed models (GLMMs) with associated family and link functions and fixed and random effects for each biotic response variable.

Response	Model	Family	Link	Fixed effects	Random effects	Variance explained
Richness						
Macroinvertebrate taxa richness	GLM	Gaussian		IC + [*predictor*]		R2
Fish species richness	GLM	Poisson		IC + [*predictor*]		pseudo-R2
Flow traits						
Macroinvertebrate flow traits, rel abund (%)	GLMM	binomial	logit	IC + [*predictor*]	1 | UniqueID	conditional-R2
Fish, fluvial rel abund (%)	GLMM	binomial	logit	IC + [*predictor*]	1 | UniqueID	conditional-R2
Thermal traits						
Macroinvertebrates, coldwater rel abund (%)	GLMM	binomial	logit	IC + [*predictor*]	1 | UniqueID	conditional-R2
Fish, coldwater rel abund (%)	GLMM	binomial	logit	IC + [*predictor*]	1 | UniqueID	conditional-R2
Tolerance						
Macroinvertebrate tolerance index	GLM	Gaussian		IC + [*predictor*]		R2
Fish, intolerant rel abund (%)	GLMM	binomial	logit	IC + [*predictor*]	1 | UniqueID	conditional-R2

Table 2.2. Summary statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) for predictor variables within each group by impervious cover band (very low = 1–4%, low = 7–10%) at 40 sites across Massachusetts, sampled during 2014–2016.

			Very-low band					Low band				
Category	Predictor variable	Units	Min	Max	Mean	SD	CV	Min	Max	Mean	SD	CV
Habitat												
	Bankfull area, mean	m2	0.9	9.5	3.9	2.34	0.60	1.4	7.5	3.4	1.74	0.51
	Bankfull area, cv	unitless	0.1	0.6	0.3	0.14	0.46	0.1	0.7	0.3	0.16	0.51
	Bankfull width, cv	unitless	0.0	0.4	0.2	0.10	0.43	0.1	0.5	0.2	0.12	0.50
	Pool habitat	% of reach	0.0	70.7	18.8	23.60	1.25	0.0	57.0	14.8	18.32	1.24
	Habitat unit transitions	no. of trans.	0.0	14.0	6.7	4.36	0.66	0.0	11.0	6.1	3.49	0.57
	Sediment, D16	mm	1.0	56.3	7.9	13.56	1.72	1.0	42.0	5.0	9.03	1.79
	Sediment, heterogeneity	unitless	1.0	31.4	4.5	6.58	1.46	1.0	8.5	2.9	1.72	0.59
	Sediment, sorting (stnd dev)	unitless	0.0	3.7	1.8	1.01	0.56	0.0	2.8	1.6	0.90	0.55
	Embeddedness	%	0.0	54.0	12.8	14.43	1.13	0.7	31.0	17.2	10.22	0.60
	Banks, vegetated	% of reach	17.0	82.5	52.8	16.80	0.32	38.8	93.1	56.1	13.29	0.24
	Banks, eroded	% of reach	16.8	83.8	44.8	21.49	0.48	7.8	79.5	46.1	19.13	0.41
	Banks, undercut	%	0.0	87.5	35.7	29.08	0.81	0.0	80.0	26.3	18.94	0.72
	Depositional features	% of reach	0.0	67.3	18.7	17.44	0.94	0.0	55.3	16.2	17.07	1.06
	Large wood, volume		0.0	49.8	7.2	13.04	1.80	0.0	8.2	1.6	2.14	1.30
Flow												
	Width:depth ratio, mean	unitless	8.2	29.3	17.7	5.69	0.32	8.0	27.3	16.6	5.71	0.34
	Width:depth ratio, cv	unitless	0.2	0.6	0.3	0.14	0.40	0.1	0.6	0.3	0.15	0.47
	Entrenchment, mean	unitless	1.7	5.6	2.8	1.02	0.36	1.3	4.9	2.9	0.92	0.31
	Entrenchment, cv	unitless	0.1	0.6	0.3	0.11	0.38	0.1	0.6	0.3	0.18	0.60
	Stream power		2.8	421.8	91.9	107.13	1.17	1.0	200.1	53.7	54.86	1.02
Temperature												
	Canopy cover	%	15.5	94.3	65.7	29.77	0.45	0.4	91.6	67.2	23.51	0.35
	Riparian vegetation		0.7	60.8	29.0	17.62	0.61	0.7	61.3	25.4	14.07	0.56
	Mean summer daily max temp	°C	13.8	25.1	20.7	2.55	0.12	19.6	26.5	22.3	1.91	0.09
	Mean summer daily temp range	°C	1.2	4.0	2.8	0.75	0.27	2.1	6.6	3.1	1.07	0.34
Water quality												
	Dissolved oxygen, mean	mg/L	5.3	10.4	8.4	1.42	0.17	5.7	11.6	8.3	1.52	0.18
	Dissolved oxygen, cv	unitless	0.1	0.6	0.3	0.12	0.41	0.1	0.6	0.3	0.11	0.40
	Specific conductance, mean	µS/cm	59.5	590.5	224.0	121.33	0.54	205.1	974.5	387.5	175.82	0.45
	Specific conductance, cv	unitless	0.1	0.6	0.2	0.11	0.47	0.1	0.6	0.3	0.17	0.66
	Nitrate, mean	mg/L	0.2	27.2	6.3	7.83	1.25	0.8	14.0	3.7	3.32	0.90

Table 2.3 Predictors with the lowest AICc from model selection within each reach-scale predictor category (Appendix H) are shown with the directionality (estimate) and variance explained (R^2) for impervious (IC) and the additional predictor (pred) in each biotic response model. Models were run for: both bands (*n* = 40), very-low band (1–4%, *n* = 20), and low band (7–10%, *n* = 20).

Response group	Both bands					Very-low band					Low band				
Response metric		Estimate					Estimate					Estimate			
Predictor category	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2
Richness															
Macroinvertebrate taxa richness															
	Impervious	-		0.10		Impervious	-		0.02		Impervious	-		0.12	
Habitat	Sediment, D16	-	-	0.20	0.11	Depositional features	-	-	0.18	0.16	**Sediment, D16**	**-**	**-**	**0.47**	**0.35**
Flow	Entrenchment, mean	-	+	0.13	0.03	Entrenchment, mean	-	+	0.13	0.11	Stream power	-	-	0.22	0.10
Temperature	Mean summer daily max temp	-	-	0.16	0.06	Canopy cover	-	-	0.19	0.17	Mean summer daily max temp	-	-	0.34	0.22
Water quality	**Nitrate, mean**	**-**	**+**	**0.22**	**0.13**	**Nitrate, mean**	**+**	**+**	**0.27**	**0.25**	Specific conductance, mean	-	-	0.20	0.09
Fish species richness															
	Impervious	-		0.13		Impervious	-		0.00		Impervious	-		0.18	
Habitat	Depositional features	-	+	0.18	0.05	**Banks, vegetated**	**+**	**+**	**0.40**	**0.39**	Depositional features	-	-	0.37	0.19
Flow	**Entrenchment, cv**	**-**	**+**	**0.27**	**0.14**	Width:depth ratio, mean	-	+	0.10	0.09	**Entrenchment, cv**	**-**	**-**	**0.48**	**0.30**
Temperature	Mean summer daily temp range	-	+	0.14	0.01	Mean summer daily temp range	-	+	0.12	0.12	Mean summer daily temp range	-	+	0.19	0.00
Water quality	Dissolved oxygen, mean	-	+	0.24	0.11	Dissolved oxygen, mean	-	+	0.26	0.25	Specific conductance, mean	-	+	0.36	0.17
Flow traits															
Macroinvertebrate flow traits, rel abund (%)															
	Impervious	+		0.00		Impervious	+		0.01		Impervious	+		0.02	
Habitat	Bankfull area, cv	+	+	0.04	0.04	**Depositional features**	**+**	**+**	**0.05**	**0.04**	**Bankfull area, cv**	**+**	**+**	**0.22**	**0.20**
Flow	Entrenchment, mean	+	-	0.01	0.01	Entrenchment, mean	+	-	0.03	0.02	Stream power	+	+	0.08	0.05
Temperature	**Mean summer daily max temp**	**-**	**+**	**0.05**	**0.04**	Mean summer daily max temp	+	+	0.02	0.01	Mean summer daily max temp	+	+	0.14	0.12
Water quality	Nitrate, mean	-	-	0.03	0.03	Nitrate, mean	+	-	0.05	0.04	Dissolved oxygen, cv	+	-	0.08	0.06
Fish, fluvial rel abund (%)															
	Impervious	-		0.16		Impervious	-		0.00		Impervious	-		0.01	
Habitat	Habitat transitions	-	+	0.22	0.06	**Sediment, D16**	**-**	**+**	**0.13**	**0.13**	Banks, vegetated	-	-	0.16	0.15
Flow	Stream power	-	+	0.25	0.09	Stream power	-	+	0.12	0.11	Width:depth ratio, cv	-	+	0.39	0.37
Temperature	Riparian vegetation	-	+	0.21	0.05	Riparian vegetation	-	+	0.05	0.04	Riparian vegetation	+	+	0.13	0.11
Water quality	**Dissolved oxygen, mean**	**-**	**+**	**0.33**	**0.17**	Specific conductance, mean	-	+	0.11	0.11	**Dissolved oxygen, mean**	**-**	**+**	**0.46**	**0.45**

Table 2.3, continued

Response group	Both bands					Very-low band					Low band				
Response metric		Estimate					Estimate					Estimate			
Predictor category	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2
Thermal traits															
Macroinvertebrates, coldwater rel abund (%)															
	Impervious	-		0.03		Impervious	-		0.03		Impervious	-		0.00	
Habitat	**Sediment, D16**	**-**	**-**	**0.06**	**0.03**	**Bankfull width, cv**	**-**	**+**	**0.06**	**0.03**	**Large wood, volume**	**-**	**-**	**0.11**	**0.11**
Flow	Width:depth ratio, mean	-	-	0.05	0.02	Stream power	-	-	0.06	0.03	Width:depth ratio, mean	-	-	0.10	0.10
Temperature	Riparian vegetation	-	-	0.04	0.02	Riparian vegetation	-	-	0.04	0.01	Riparian vegetation	-	-	0.04	0.04
Water quality	Specific conductance, mean	-	+	0.04	0.02	Specific conductance, cv	-	-	0.06	0.02	Specific conductance, mean	-	+	0.08	0.08
Fish, coldwater rel abund (%)															
	Impervious	-		0.14		Impervious	+		0.00		Impervious	-		0.12	
Habitat	**Large wood, volume**	**-**	**+**	**0.23**	**0.08**	**Large wood, volume**	**+**	**+**	**0.24**	**0.24**	**Sediment, heterogeneity**	**-**	**-**	**0.49**	**0.37**
Flow	Entrenchment, mean	-	-	0.20	0.05	Entrenchment, mean	+	-	0.08	0.07	Stream power	-	+	0.34	0.22
Temperature	Riparian vegetation	-	+	0.22	0.07	Mean summer daily temp range	+	-	0.10	0.09	Riparian vegetation	-	+	0.20	0.08
Water quality	Dissolved oxygen, mean	-	+	0.21	0.07	Nitrate, mean	+	+	0.07	0.06	Dissolved oxygen, mean	-	+	0.28	0.17
Tolerance															
Macroinvertebrate tolerance index															
	Impervious	+		0.06		Impervious	+		0.15		Impervious	+		0.08	
Habitat	**Embeddedness**	**+**	**-**	**0.34**	**0.28**	**Embeddedness**	**+**	**-**	**0.53**	**0.39**	Embeddedness	+	-	0.47	0.39
Flow	Entrenchment, mean	+	+	0.16	0.10	Width:depth ratio, mean	+	-	0.20	0.05	Entrenchment, mean	+	+	0.34	0.26
Temperature	Riparian vegetation	+	-	0.15	0.09	Riparian vegetation	+	-	0.26	0.12	**Mean summer daily temp range**	+	+	**0.48**	**0.40**
Water quality	Nitrate, mean	+	-	0.23	0.17	Dissolved oxygen, mean	+	-	0.38	0.23	Specific conductance, mean	+	+	0.36	0.28
Fish, intolerant rel abund (%)															
	Impervious	-		0.05		Impervious	-		0.14		Impervious	-		0.01	
Habitat	Large wood, volume	-	+	0.10	0.05	Habitat transitions	-	-	0.29	0.15	Sediment, heterogeneity	-	-	0.10	0.09
Flow	Entrenchment, cv	-	+	0.09	0.04	Width:depth ratio, mean	-	-	0.18	0.04	Stream power	-	+	0.06	0.05
Temperature	**Mean summer daily max temp**	+	**-**	**0.47**	**0.42**	**Mean summer daily max temp**	**-**	**-**	**0.56**	**0.41**	**Mean summer daily max temp**	**-**	**-**	**0.63**	**0.62**
Water quality	Nitrate, mean	-	+	0.10	0.05	Nitrate, mean	-	+	0.22	0.07	Dissolved oxygen, mean	-	+	0.10	0.09

Note: Variables with the highest R^2 for each biotic response metric in each band are highlighted in bold.

Table 2.4. Variable importance was determined through all-subsets GLMs and GLMMs for each biotic response metric. The all-subsets approach ran models for every variable combination of impervious cover and the top-performing predictor from each predictor category of habitat, flow, temperature, and water quality. Model weights (*w*) were calculated based on corrected Aikaike Information Criterion (AICc) values across all 31 models run. Variable importance was calculated for equally plausible models (< 2 ΔAICc); Σw represents the sum of model weights for each model in which the variable appeared. Higher Σw values indicate more important variables. Impervious cover is highlighted in gray.

	Both bands		Very-low band		Low band	
Response	Predictor	Σw	Predictor	Σw	Predictor	Σw
Richness						
Macroinvertebrate taxa richness						
	Nitrate, mean	0.53	Nitrate, mean	0.45	Sediment, D16	0.62
	Sediment, D16	0.35	Canopy cover	0.20	Impervious	0.53
	Impervious	0.27	Depositional features	0.14	Mean summer daily max temp	0.40
	Mean summer daily max temp	0.26	Entrenchment, mean	0.08	Specific conductance, mean	0.40
Fish species richness						
	Impervious	0.50	Banks, vegetated	0.43	Entrenchment, cv	0.47
	Entrenchment, cv	0.46	Dissolved oxygen, mean	0.22	Depositional features	0.27
	Dissolved oxygen, mean	0.40	Width:depth ratio, mean	0.10	Specific conductance, mean	0.17
	Depositional features	0.25				
Flow traits						
Macroinvertebrate flow traits, rel abund (%)						
	Mean summer daily max temp	0.51	Depositional features	0.32	Bankfull area, cv	0.52
	Bankfull area, cv	0.47	Nitrate, mean	0.31	Mean summer daily max temp	0.52
	Entrenchment, mean	0.25	Mean summer daily max temp	0.08	Stream power	0.31
	Nitrate, mean	0.20				
Fish, fluvial rel abund (%)						
	Impervious	0.76	Stream power	0.24	Width:depth ratio, cv	0.37
	Dissolved oxygen, mean	0.76	Specific conductance, mean	0.22	Dissolved oxygen, mean	0.37
	Habitat transitions	0.34	Sediment, D16	0.19		
	Riparian vegetation	0.22				
	Stream power	0.13				
Thermal traits						
Macroinvertebrates, coldwater rel abund (%)						
	Impervious	0.58	Impervious	0.44	Width:depth ratio, mean	0.41
	Sediment, D16	0.45	Bankfull width, cv	0.44	Large wood, volume	0.24
	Width:depth ratio, mean	0.32	Stream power	0.44	Specific conductance, mean	0.24
	Specific conductance, mean	0.30	Specific conductance, cv	0.44	Impervious	0.13
Fish, coldwater rel abund (%)						
	Large wood, volume	0.62	Large wood, volume	0.49	Sediment, heterogeneity	0.45
	Riparian vegetation	0.45	Mean summer daily temp range	0.13	Stream power	0.45
	Impervious	0.36	Impervious	0.12	Impervious	0.13
	Dissolved oxygen, mean	0.32				
Tolerance						
Macroinvertebrate tolerance index						
	Embeddedness	0.89	Impervious	0.63	Embeddedness	0.74
	Nitrate, mean	0.89	Embeddedness	0.63	Specific conductance, mean	0.64
	Riparian vegetation	0.57	Dissolved oxygen, mean	0.37	Impervious	0.48
	Impervious	0.48			Mean summer daily temp range	0.35
	Entrenchment, mean	0.42				
Fish, intolerant rel abund (%)						
	Mean summer daily max temp	0.54	Mean summer daily max temp	0.54	Mean summer daily max temp	0.56
	Entrenchment, cv	0.14	Impervious	0.34	Dissolved oxygen, mean	0.33
	Nitrate, mean	0.13				

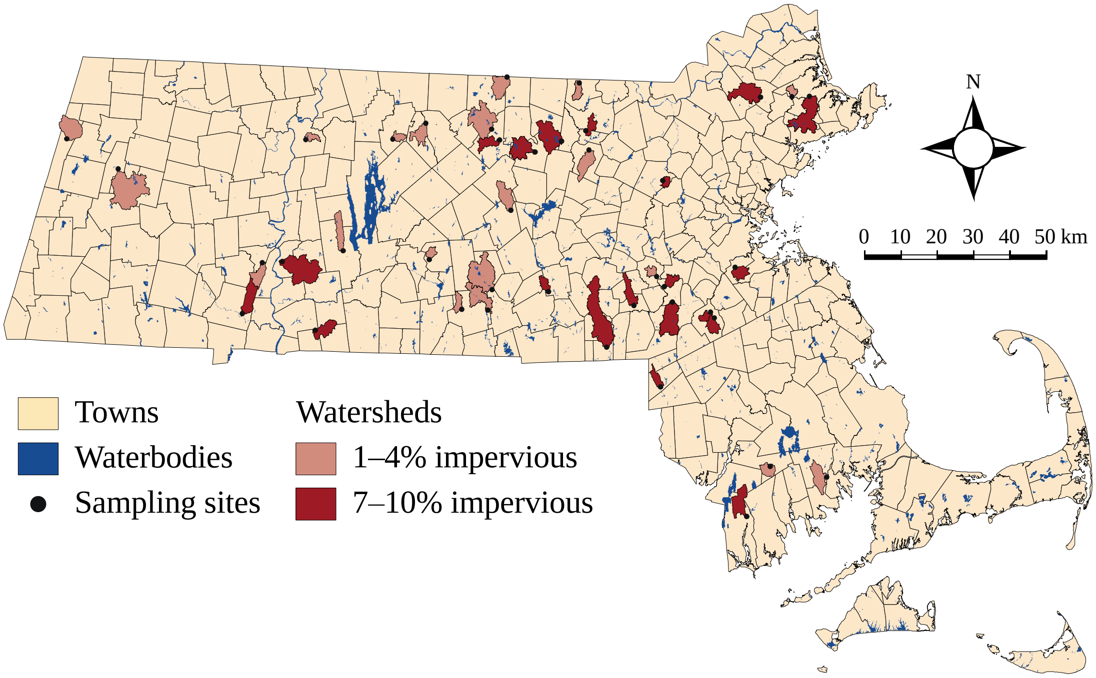


Figure 2.1. Forty sites sampled across Massachusetts within two bands of impervious cover: 1–4% (*n* = 20; pink) and 7–10% (*n* = 20; red) during 2014–2016. Major waterbodies (large rivers, lakes; blue) and town boundaries are also shown.

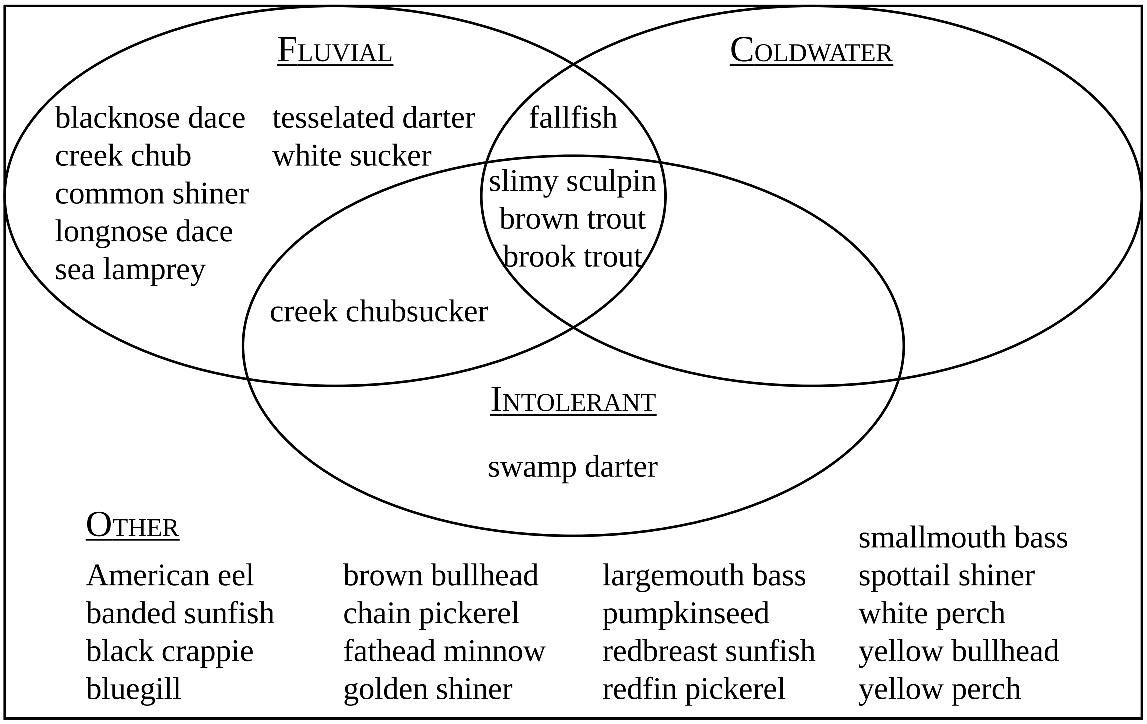


Figure 2.2. Overlap among fish species with fluvial, coldwater, and intolerant traits. Species that do not possess any of these traits, and thus were not included in the suite of flow, thermal, and tolerance response variables, are listed as “other”.

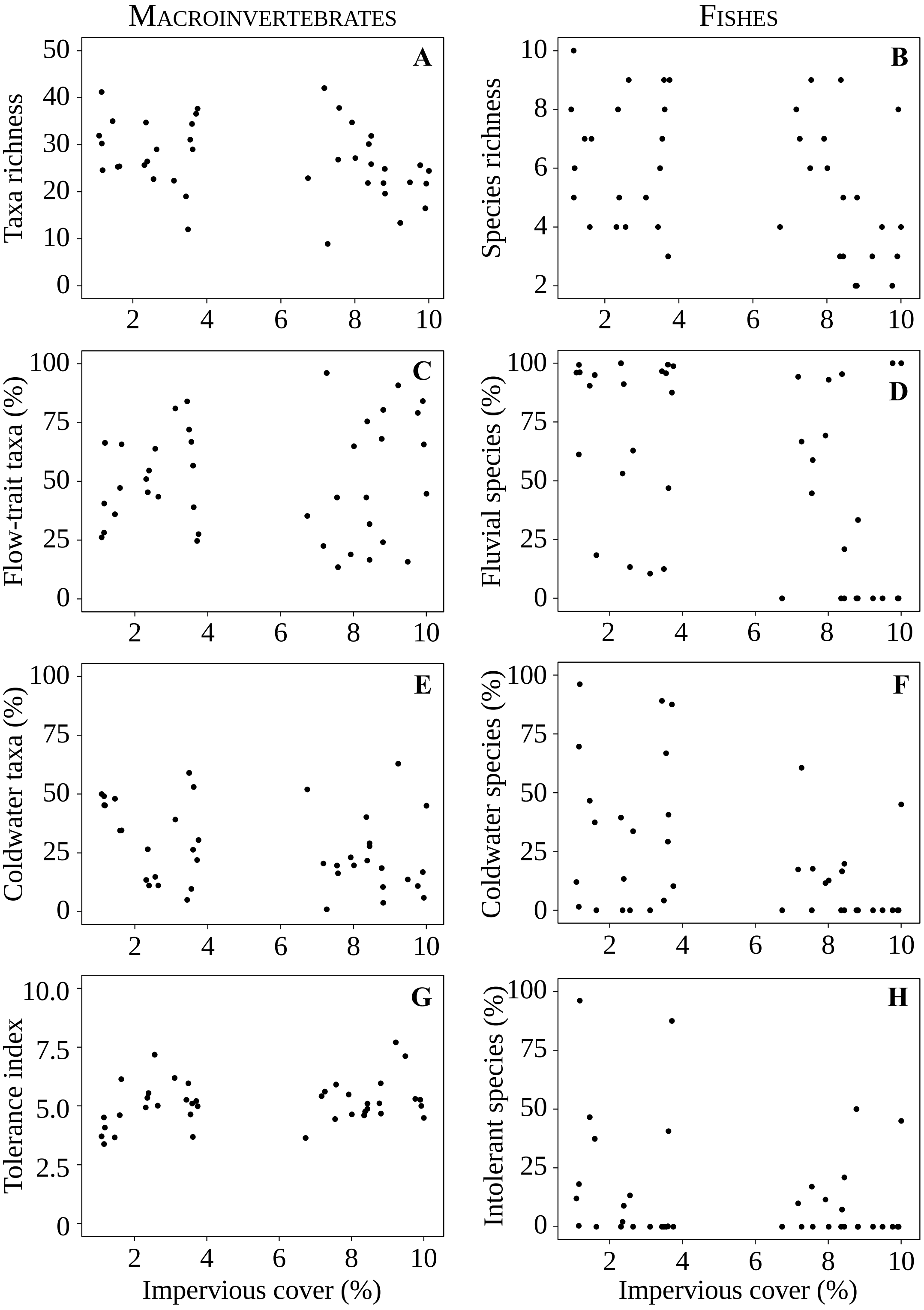
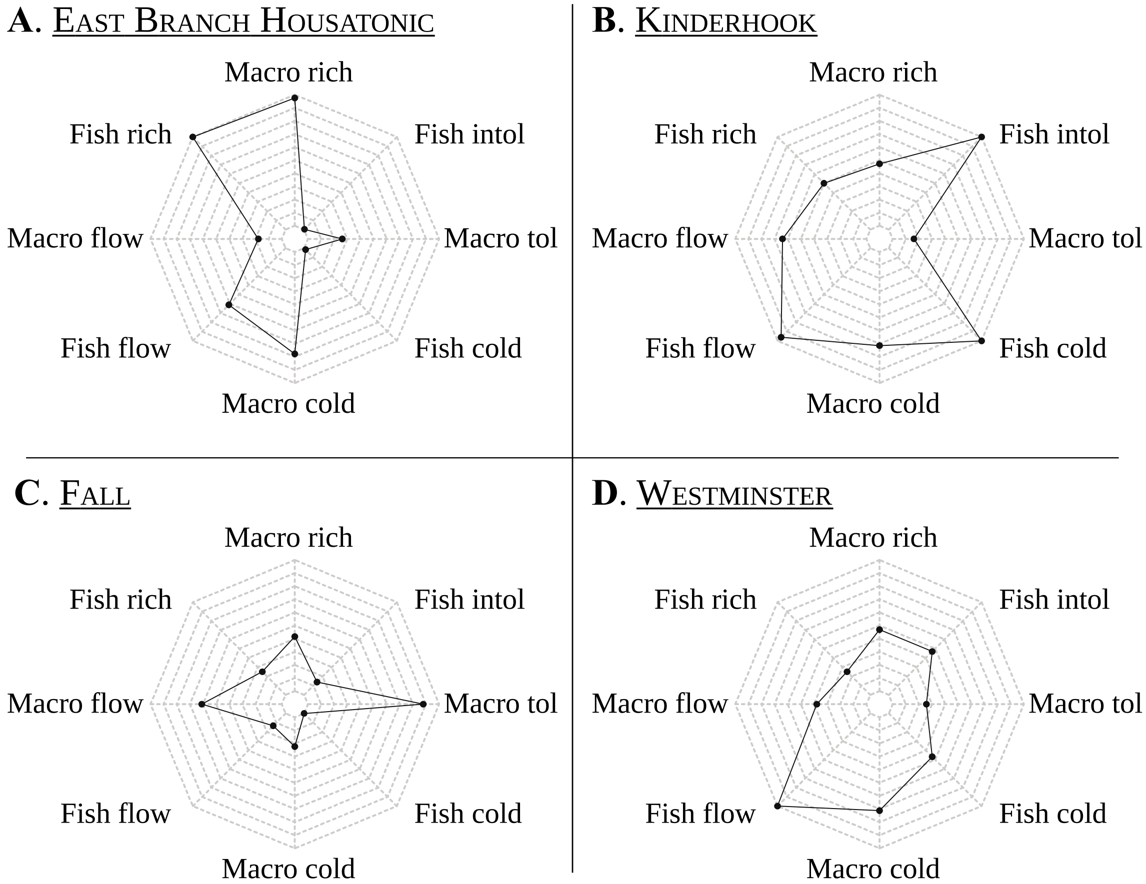


Figure 2.3. Scatterplots of the relationship between impervious cover and biotic response variables: macroinvertebrate taxa richness (A), fish species richness (B), macroinvertebrate flow traits (C), fluvial fishes (D), coldwater macroinvertebrates (E), coldwater fishes (F), macroinvertebrate tolerance index (G), and intolerant fishes (H).


A. East Branch Housatonic

B. Kinderhook

C. Fall

D. Westminster

Figure 2.4. Spider plots displaying biotic response variables at four selected sites: East Branch Housatonic (A), Kinderhook (B), Fall (C), and Westminster (D). Counterclockwise from top center around each plot, the response variables are macroinvertebrate richness, fish richness, macroinvertebrate flow traits, fish flow traits, macroinvertebrate thermal traits (coldwater), fish thermal traits (coldwater), macroinvertebrate tolerance index, and fish intolerant. Black dots show the relative value for each response variable. Dots closer to the center of the plot indicate low values; dots further away from the center and near the outer ring indicate high values. All plots are scaled such that the center represents the minimum value found across all 40 sites, while the outer ring represents the maximum value found across all 40 sites.

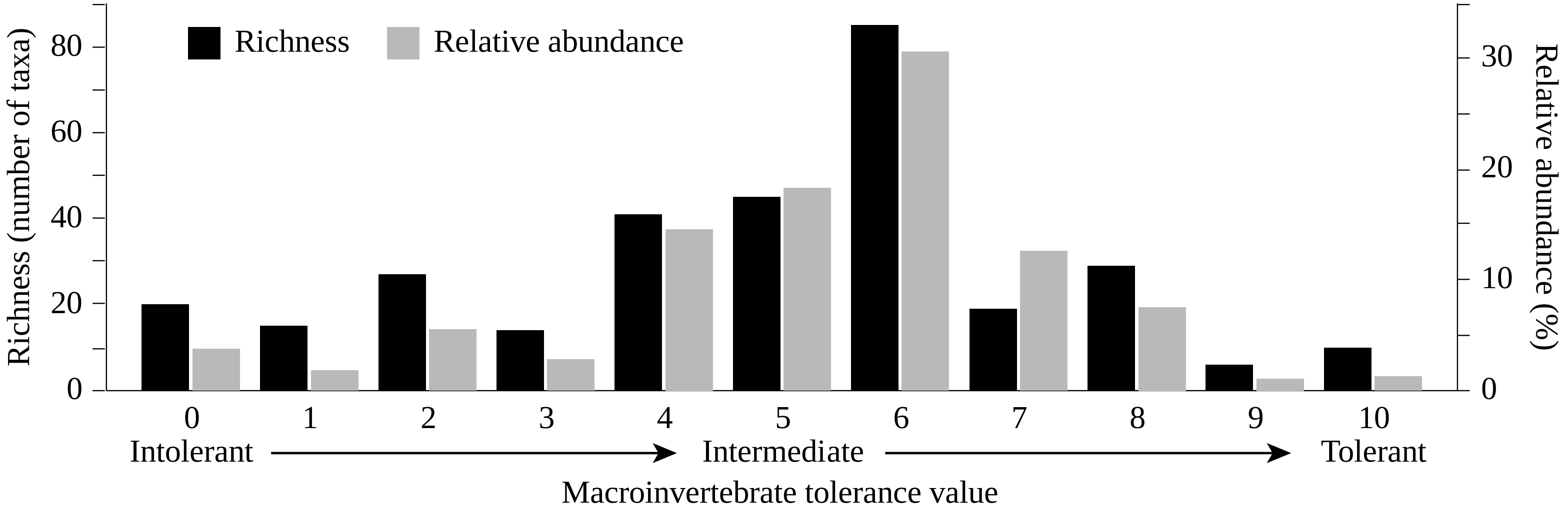
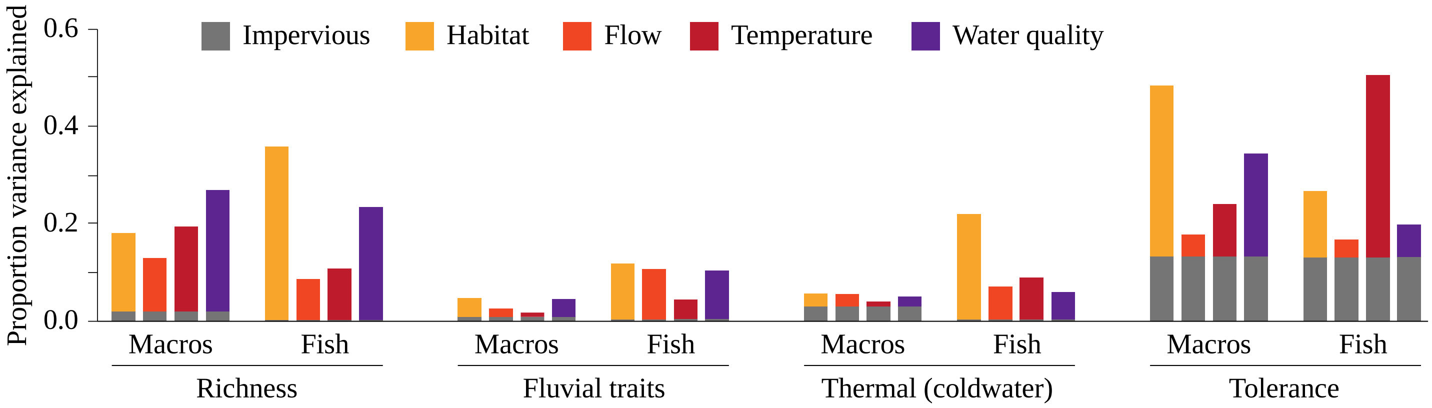


Figure 2.5. Histograms of macroinvertebrate taxa richness (black) and relative abundance (gray) along the tolerance gradient from intolerant (0) to tolerant (10).

A. Very-Low Band



B. Low Band

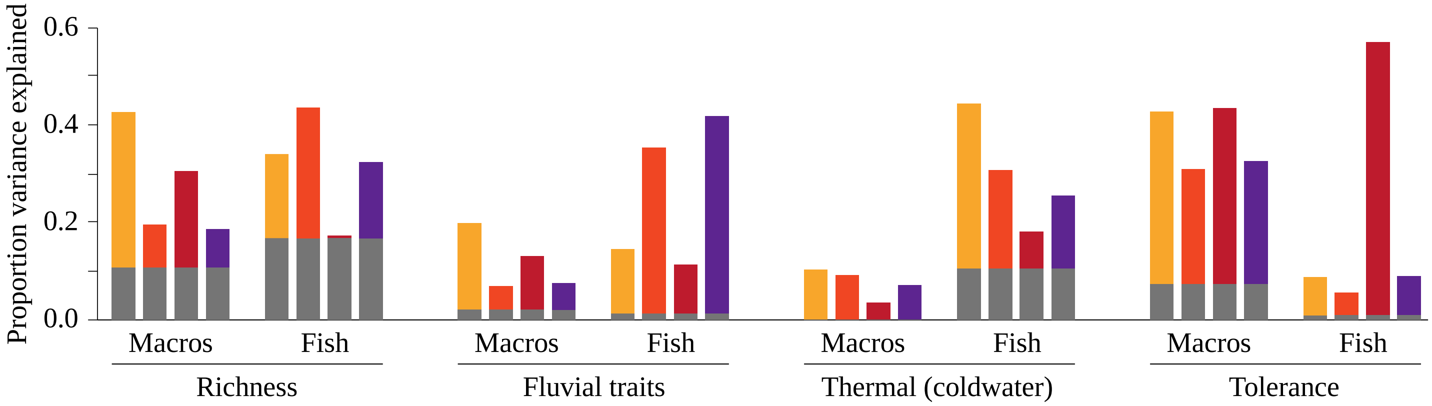


Figure 2.6. Additional variance explained by reach-scale predictors within predictor categories of habitat, flow, temperature, and water quality, for (A) very-low (1–4%) and (B) low (7–10%) impervious bands.

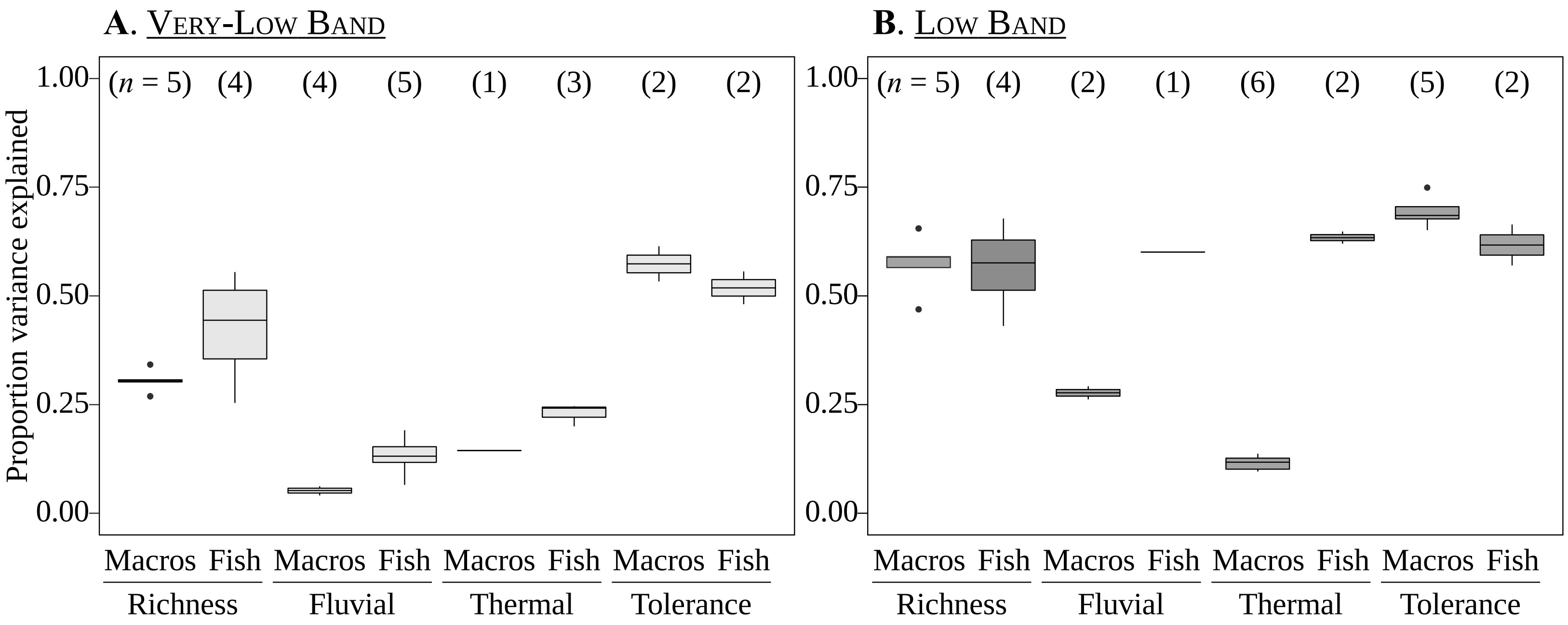


Figure 2.7 Box plots for variance explained by equally plausible models within the very-low band (A) and low band (B). Equally plausible models (< 2 AICc) are available in Appendix I.

CHAPTER 3

WATERSHED-SCALE FACTORS EXPLAIN ADDITIONAL VARIANCE IN BIOTIC ASSEMBLAGES OF URBAN STREAMS

3.1 Introduction

As urbanization increases in a watershed, the integrity of stream biotic assemblages declines (see reviews in Walsh et al. 2005, Wenger et al. 2009). This relationship was depicted by Schueler et al. (2009) as a wedge-shaped curve, for which biotic condition is consistently degraded at higher levels of watershed impervious cover, while biotic condition ranges from poor to excellent at lower levels of watershed impervious cover. In order to appropriately manage the effects of urban development on water resources, it is necessary to understand the factors that drive this biotic variability at low levels of impervious cover. While watershed impervious cover is recognized as an important stressor to fish and macroinvertebrate assemblages (Brabec et al. 2002), other watershed-scale factors—reflecting both natural characteristics and anthropogenic disturbance—may affect whether biotic assemblages reflect good or poor condition.

Natural characteristics related to the drainage area, climate, and geology create an environmental template that affects stream biotic assemblages, and may explain variation in biotic condition observed at low levels of impervious cover. Climate—both temperature and precipitation—affects components of the hydrological cycle, including base flow, flow permanence, runoff, flashiness, snowmelt, and evapotranspiration (Hale et al. 2016), which in turn influences fishes (Poff and Zimmerman 2010) and macroinvertebrates (Konrad et al. 2008). Regional geology modifies these hydrological responses and the interaction between surface waters and groundwater, and can also dictate reach-scale slope, bed texture, and other geomorphic factors that directly influence stream biota (Montgomery 1999).

Catchment land uses, such as open water, wetland, and forest, provide ecosystem functions that affect biotic assemblages. Wetland cover is often associated with higher biotic condition potentially due to its role in slowing flows, storing water in floodplains, filtering contaminants, and acting as sites of nutrient transformation, including denitrification (Groffman et al. 2002). The extent of forest cover in the watershed is also associated with higher biotic condition (Allan 2004). Forest cover modifies hydrological responses, including evapotranspiration, that influence stream flows (Gordon et al. 2004). When located along riparian corridors, forest cover shades the channel, contributes wood and leaf litter, and stabilizes stream banks (Hession et al. 2003).

Historical land use may also influence biotic condition at low levels of impervious cover, due to the impact of legacy effects (Harding et al. 1998). Forest or agricultural land uses in the watershed prior to urban development are significant predictors of biotic responses (Brown et al. 2009, Cuffney et al. 2011). Cappiella et al. (2012) noted that biota appeared to be more degraded when urbanization occurred on forested land than agricultural land, since sensitive species were already lost due to agriculture prior to development. Utz et al. (2009) also found that macroinvertebrates did not respond as severely to agriculture as to urbanization, potentially for the same reason: that sensitive species had already been lost after decades or centuries of agricultural use, while the remaining taxa had adapted to such alteration. Prior land use history can potentially confer resistance for biotic communities, particularly when urban infrastructure effectively limits or reduces nutrient inputs relative to current or past conditions (Utz et al. 2016).

Dams and water withdrawals alter flow and thermal regimes independent of impervious cover, although their presence and magnitude potentially also interact with existing impervious cover to influence biotic condition. Water withdrawals and wastewater discharge can also lead to different hydrological responses (Bhaskar et al. 2016). Groundwater pumping, such as for water supply or to protect urban infrastructure (e.g., subway tunnels), can result in lower water tables in urban areas. Wastewater treatment plant inputs provide higher flows downstream of discharge points, which may mask or interact with water withdrawals; this may create heterogeneous base flow conditions on smaller scales even if base flow in the watershed overall remains unchanged (Brandes et al. 2005, Weiskel et al. 2007). Water infrastructure can contribute to either increased or decreased base flow based on leakages from or into sewer systems, and import or export of water outside the watershed (Bhaskar et al. 2016). In some cases, as in Baltimore, Maryland, groundwater leakage into sanitary sewers had greater influence on base flow than impervious cover (Bhaskar and Welty 2012, Bhaskar et al. 2016), which might account for the variability in base flows measured there (Schwartz and Smith 2014). Water infrastructure can also contribute to nutrient loading in urban systems, such as through leaky wastewater sewers or combined sewer overflows (Hale et al. 2016).

Metrics that decompose total impervious area into finer categories can potentially lead to better understanding of mechanisms of impairment, as well as explain variability in ecological responses. One such measure is effective impervious surface, or direct hydraulic connection of impervious surfaces to streams via pipe networks, which has emerged as a strong predictor of stream degradation due to its role in driving hydrological alteration (Alley and Veenhuis 1983, Booth and Jackson 1997, Wang et al. 2001, Brabec et al. 2002, Walsh et al. 2005, Roy and Shuster 2009, Vietz et al. 2014). Where water that falls on impervious surfaces is routed directly to the stream channel, it bypasses interaction with landscape features such as geology, soils, or riparian vegetation that would potentially lead to different responses based on the regional and physicochemical template (Utz et al. 2011). The relative proportion of effective impervious cover may be more important at low levels of impervious cover, since most impervious cover is connected at the high end of the urban gradient (Alberti et al. 2007). Specific types of impervious cover may also explain variability in responses. For example, Alberti (2005) and Alberti et al. (2007) found that road density and road crossings were significant predictors of benthic index of biotic integrity (B-IBI) in the Puget Sound, Washington. Roads can also serve as barriers for fish, such as when culverts at road-stream crossings are undersized, perched, devoid of sediment, or lack stream flow (Trombulak and Frissell 2000). Sediment loading from roads has been shown to favor silt-tolerant macroinvertebrate and fish species (Angermeir et al. 2004). Lastly, the location and spatial arrangement of impervious surfaces also affects stream impairment. Landscape position of urban development can differentially affect baseflow conditions, particularly when urban development is located in areas of high groundwater recharge (Bhaskar et al. 2016).

These natural and anthropogenic watershed characteristics formed the basis of my hypotheses of factors that may explain differences in biotic condition in watersheds with similar levels of low impervious cover. Specifically, I asked:

1. Which watershed-scale predictors—representing natural characteristics, land cover, flow alteration, and other measures of urbanization—best explain biotic condition at sites with similar levels of impervious cover?
2. How do watershed-scale predictors act in combination to explain biotic condition at sites with similar levels of impervious cover?

These questions were asked for two taxonomic groups (macroinvertebrates and fishes) and several biotic response metrics (richness, flow traits, thermal traits, tolerance), allowing me to compare responses across taxa and metrics. Finally, the streams studied had very low (1–4%) or low (7–10%) impervious cover, levels where biotic condition was not expected to be consistently degraded. These two impervious cover levels allowed me to test whether factors explaining variability differed based on total impervious cover. Ultimately, this study aimed to provide insights as to what watershed characteristics, in combination with impervious cover, are likely to lead to more degraded biotic conditions, and which characteristics confer biotic resistance to urbanization, thus guiding management decisions prioritizing areas for protection or restoration.

3.2 Methods

3.2.1 Study area

This study was conducted in Massachusetts, which spans three main ecoregions: the Northeastern Highlands in the western and north-central parts of the state, the

Northeastern Coastal Zone in the eastern part of the state, and Cape Cod and the Islands along the coast (Hall et al. 2002). The Northeastern Highlands are higher elevation (60–1014 m) mountains, whereas the Northeastern Coastal Zone primarily consists of lower elevation (0–364 m) lowlands and rolling hills. Climatic conditions—characterized by warm summers and cold snowy winters— are generally similar across the state, with slight variations by ecoregion: the average annual temperature is 7.3°C in the Northeastern Highlands compared to 9.4°C in the Northeastern Coastal Zone, and the average annual precipitation is 119 cm in the Northeastern Highlands compared to 117 cm in the Northeastern Coastal Zone (Hall et al. 2002). Cape Cod and the Islands (Martha's Vineyard and Nantucket were not included in this study since simulated stream flows were not available for these areas at the time of study design, which led to their omission from other studies characterizing flow and fish communities in Massachusetts (Armstrong et al. 2011). Geology across the state is mostly comprised of granitic and metamorphic bedrock, with some calcareous or moderately calcareous bedrock in the west. Surficial geology is typically dominated by glacial till, with higher amounts of sand and gravel in the east. Soils are acidic and nutrient-poor (Hall et al. 2002).

The Massachusetts landscape has a long history of human alteration from agriculture, dams and water withdrawals, industrial use, and urban development. Agricultural development peaked in the nineteenth century, when about half of the state land area was used for pasture, hay, or cultivated crops; this was associated with a decline in forested land area (Hall et al. 2002). Concurrent with agricultural development in the nineteenth century was rapid industrial development in New England. Rivers and streams were dammed to provide power for mills; as a result, New England has the highest density of dams in the country (0.015 dams km^{-2}) (Graf 1999), with more than 14,000 dams throughout the region (Magilligan et al. 2016). After reaching its height in the nineteenth century, subsequent declines in agricultural land use led to increases in forested land cover through the mid-twentieth century, after which forested land continued to increase in the Northeastern Highlands, but decreased in the Northeastern Coastal Zone as more land was developed for residential and commercial purposes (Hall et al. 2002).

Current land use patterns reflect both historical uses and the influence of geology, topography, and water features. The population of Massachusetts is approximately 6.8 million statewide, 667,000 of which are concentrated Boston, located on the coast in eastern Massachusetts (U.S. Census Bureau 2015). Urban sprawl radiates from the city center into the surrounding land, which is becoming increasingly developed. Agriculture is concentrated in the fertile floodplains of the Connecticut River Valley. The Berkshires in western Massachusetts remain the least developed region with the most forest cover in the state.

3.2.2 Site selection

Forty stream sites throughout Massachusetts were chosen for this study (Figure 3.1). Contributing areas were delineated for each sampling site using ArcGIS 10.3. Watersheds met several criteria: (1) independent, without overlapping basins; (2) between 5–80 km^2 area; (3) either 1–4% (n = 20) or 7–10% (n = 20) impervious cover, as calculated based on the 2011 National Land Cover Dataset (NLCD); and (4) less than

20% agricultural land use per the 2011 NLCD. Additional information regarding the calculations and rationale for each criterion are provided in Chapter 2, Section 2.2.2.

All sites had both macroinvertebrate and fish assemblage data collected within the past 11 years (2005–2015). Assemblage data were accessed from existing databases created by the Massachusetts Department of Environmental Protection (MDEP) and Massachusetts Division of Fisheries and Wildlife (MDFW). For 17 sites, data for both macroinvertebrates and fishes were collected by MDEP during the same sampling season. For 4 sites, data were collected at the same site, but by different agencies during different sampling years. For the remaining 19 sites, data were available from one agency and additional macroinvertebrate or fish sampling was conducted by MDFW and University of Massachusetts Amherst in 2014–2015 following agency protocols such that each site ultimately had both macroinvertebrate and fish data.

3.2.3 Biotic assemblages

Macroinvertebrates were collected with a rectangular-frame kick net in 10 riffles, which were aggregated into one sample for each site. Samples were sorted and identified to the lowest feasible level (often genus or species) in the lab by MDEP or Cole Ecological, Inc. Macroinvertebrate samples collected 2005–2011 were subsampled to 100 individuals, whereas samples collected 2012–2015 were subsampled to 300 individuals. Subsamples that were 300-count were rarefied using the vegan package in R (Oksanen et al. 2016) to standardize with 100-counts subsamples (Gotelli and Colwell 2001).

Several macroinvertebrate metrics were calculated, including: taxa richness, relative abundance of taxa with flow-adapted traits, relative abundance of coldwater taxa, and a tolerance index. Flow-adapted traits were assessed using a combination of rheophily (erosional, erosional or depositional, depositional), shape (streamlined, not streamlined), swimming ability (none, weak, strong), and attachment (none, some, both) categories available in the appendices of Poff et al. (2006b) and trait databases created by the U.S. Geological Survey (Vieira et al. 2006), and U.S. Environmental Protection Agency (US EPA 2012, 2016). Multiple traits were aggregated into a single flow-trait metric based on presence of 2 of 4 of the following traits: erosional rheophily, streamlined shape, strong swimming ability, and some attachment (Appendix C.2). Macroinvertebrates were also categorized into thermal traits (cold stenothermal/cool eurythermal, cool/warm eurythermal, and warm eurythermal) using the same sources as flow traits. The relative abundance of macroinvertebrate taxa classified as cold stenothermal/cool eurythermal was calculated. The tolerance index was calculated based on the methods established in Hilsenhoff (1998), for which each taxon is assigned a tolerance value of 0–10 from least to most tolerant, and an aggregate score is calculated for the assemblage present.

Fishes were sampled by MDFW, MDEP, and University of Massachusetts Amherst using single-pass electrofishing and identified to species level. Fish metrics were calculated for species richness and relative abundances of fluvial fishes, coldwater fishes, and intolerant fishes. Fish were classified based on MDFW categories; classifications for each species can be found in Appendix C.3.

3.2.4 Watershed variables

Watershed characteristics were assessed with ArcGIS 10.3, using data layers available through National Land Cover Database (NLCD) and MassGIS (Table 3.1). Variables were classified into four predictor categories: natural characteristics, land cover, flow alteration, and other urban and impervious measures. Natural characteristics of each site included drainage area, elevation, precipitation, air temperature, and surficial geology. Drainage area was delineated for each unique sampling site with National Hydrography Dataset (NHD) flowlines; basin and site elevation were calculated from Digital Elevation Models (DEMs). Precipitation and air temperature were calculated from PRISM (Parameter-elevation Relationships on Independent Slopes Model) models developed by Oregon State University (Daly et al. 2008). Surficial geology was represented by the percent sand and gravel in the basin, as this variable is thought to reflect groundwater contributions to the basin (Armstrong et al. 2011).

Current and historical land use for forest, wetland, open water, and agriculture was assessed at watershed and riparian buffer scales. Current land use in the watershed was calculated with 2011 and 2006 NLCD, to match the biotic sampling window of 2005–2015. Current land use in the buffer was calculated with 2011 NLCD; buffers were 120-m wide, for the entire stream network upstream of the sampling site. Historical agricultural use was represented by 1992 NLCD data: across the four years of historical land use data available for Massachusetts (1992 from NLCD; 1971, 1985, and 1999 from MassGIS), agricultural use peaked at all 40 sites during 1992 (Appendix J.2); hence that year was used to represent the greatest historical coverage. Since the land cover classification schemes differ between NLCD and MassGIS and across years, land uses were aggregated into categories comparable to the 2011 NLCD classification scheme (Appendix J.1).

The flow alteration category includes metrics related to dams and water withdrawals. Several metrics assessed the role of dams on the landscape: dam density per watershed area, dam density per stream length in the watershed, longest undammed flow path distance (both upstream and downstream, encompassing the site), and distance from sampling location to nearest upstream dam. Dam data were accessed from MassGIS, which derived their data from the Massachusetts Office of Dam Safety. Flow alterations were assessed using data simulations based on the Sustainable Yield Estimator (Archfield et al. 2010). The SYE output is the monthly 'sustainable yield' volume, which is the maximum volume of water that can be withdrawn without depleting a steam lower than a user-specified value (i.e., the target streamflow value). Since Armstrong et al. (2011) found summer flows to be most important for fish assemblages in Massachusetts, the June–September unaltered, altered, and percent difference between unaltered and altered flows were used, as well as the mean annual percent difference between unaltered and altered flows.

Different aspects of urbanization and impervious cover were quantified in addition to total watershed impervious cover. Impervious cover within a 120-m buffer was calculated from 2011 NLCD as well as a 10-m aggregation between 2011 NLCD (30-m resolution) and 2005 MassGIS (1-m resolution). Recent change in watershed impervious cover was calculated as the difference in impervious cover between 2006 and 2011 NLCD. Population and housing density were assessed for each watershed. Roads were assessed as road density per watershed area, as well as the number and density of road-stream crossings in the watershed. An algorithm was developed by Matt Baker (University of Maryland Baltimore County) and Lance Ostiguy (USGS New England Water Science Center) to quantify flow- and distance-weighted impervious cover. Since most flow- and distance-weighting metrics were highly correlated, one distance metric and one flow metric were used for this analysis: relative flow length distance to the sampling station (FL) and gradient-to-length ratio (GLR), which relates the flow gradient with the flow length distribution as a topographic estimate of water residence time (M. Baker, *pers comm*.). Four weights were used for FL and GLR: 0.5, 1.0, 1.5, and 2.0, for which larger values have greater emphasis on proximate locations. Distances use weights as a negative power, while flow weights use weights as a positive power (*sensu* King et al. 2005).

3.2.5 Statistical analyses

A series of modeling steps were performed to determine the watershed-scale variables that best explained each biotic response variable. Generalized linear models were developed for each biotic response metric (Zuur et al. 2012) using the stats package in R (R Core Team 2016). GLM distributions were chosen based on the characteristics of the response metric: macroinvertebrate richness and macroinvertebrate tolerance used a Gaussian (i.e., normal) distribution; fish richness used a Poisson distribution appropriate for zero-bounded count data; and relative abundances of macroinvertebrate and fish flow traits, coldwater macroinvertebrates and fishes, and intolerant fishes used a binomial distribution with logit link function appropriate for proportional data. The Shapiro-Wilk test was used to assess normality in the distributions of response variables.

Macroinvertebrate richness and macroinvertebrate tolerance were normally distributed; the other response variables had non-normal distributions. Log transformations did not improve normality of the remaining response variables and thus were not used. Binomial GLMs had extreme overdispersion (ratio of residual deviance to degrees of freedom, for which a value greater than 1 indicates overdispersion; Warton and Hui 2011); thus, generalized linear mixed models (GLMMs) with a random effect for sampling site were run for all proportional response variables using the lme4 package in R (Bates et al. 2015).

In order to reduce the number of predictor variables for models based on the limited sample size ($n = 20$ for each band), variable selection occurred in several steps. First, predictor variables within each predictor category (natural characteristics, land cover, flow alteration, and other urban or impervious measures) were tested for collinearity based on pairwise Spearman rank correlation analysis. When pairs of variables were highly collinear ($r \geq |0.7|$), one variable was selected for subsequent analysis.

From this reduced list of predictors, GLMs and GLMMs were run with impervious cover plus each individual predictor in turn. These single-variable models were compared using Akaike's Information Criterion (AIC; Burnham et al. 2011), corrected for small sample size and penalized for the number of parameters. The predictor variable with the lowest AICc within each predictor category was retained for further analysis. This resulted in one predictor per predictor category, for a total of four predictors used in subsequent analyses.

A global model was compiled of impervious cover with the four selected predictor variables. All combinations of the five variables were run, for a total of 31 models for each biotic response variable. AICc was used for model selection among these 31 models. Model weights were calculated based on the total number of models run; model weight represents the likelihood that the chosen model is the correct model. Models within 2 ΔAICc units were considered equally plausible, competing models. Variable importance was calculated to compare amongst predictors retained within the equally plausible models. The amount of variance (i.e., R^2, pseudo-R^2, or conditional-R^2, based on the model distribution) explained in equally plausible models was used to compare models across taxonomic groups, biotic response metrics, and impervious bands.

3.3 Results

3.3.1 Site characteristics

For the 40 sites that were included in this study, the 20 sites in the very-low impervious band ranged from 1.1–3.7% watershed impervious cover, whereas the 20 sites in the low band ranged from 6.7–10.0% watershed impervious cover, according to the 2011 NLCD. One site was <7% impervious due to an error in calculations during site selection, but was still included in the low band. Drainage areas ranged from 5.8–72.1 km^2 in the very-low band and 5.3–66.3 km^2 in the low band. Agriculture ranged from 0.3–15.8% of total land cover in the very-low band and 0.0–20.4% in the low band.

3.3.2 Biotic responses

Across the 40 sites, 318 macroinvertebrate taxa and 30 fish species were sampled (Appendix B). Two macroinvertebrate taxa (0.6%) were not classified for flow traits and 46 taxa (14.5%) were not classified for thermal traits due to lack of information in existing trait databases. Of the remaining macroinvertebrate taxa, 115 taxa (36.2%) were classified as having flow-adapted traits and 88 taxa (27.7%) were coldwater. Macroinvertebrate tolerance indices for the aggregate assemblage at each site ranged from 3.4–7.7, based on a scale ranging from intolerant (0) to tolerant (10). Twelve of the 30 fish species collected were considered fluvial (fluvial dependent or fluvial specialist), four species were coldwater, and five species were intolerant.

Macroinvertebrate and fish responses were highly variable within each band of impervious cover (Table 3.2), as predicted by the impervious cover model (Schueler et al. 2009). However, all response variables—except macroinvertebrate tolerance for which the index is scaled from intolerant to tolerant—had greater variation within the low band than the very-low band. Across each response group of richness, flow traits, thermal traits, and tolerance, fish responses were more dispersed than macroinvertebrate responses, as indicated by higher coefficients of variation (Table 3.2).

Biotic metrics were not necessarily concordant between macroinvertebrate and fish taxonomic groups (Figure 3.2). Macroinvertebrate and fish richness tended to show similar assessment of condition: sites that had high macroinvertebrate richness also had high fish richness. There was general agreement between fish and macroinvertebrate metrics of coldwater taxa, albeit most taxa that were sampled were not classified as coldwater for either macroinvertebrates or fishes. Similarly, few fishes were classified as intolerant, and the macroinvertebrate tolerance index did not demonstrate much scatter across sites. In contrast, flow traits demonstrated a notable lack of concordance between taxonomic groups: sites either had high relative abundance of flow-adapted macroinvertebrate taxa or high relative abundance of fluvial fishes, but rarely both.

3.3.3 Watershed-scale predictors

Air temperatures were slightly cooler at very-low-band sites compared to low-band sites, with ranges of -0.2–5.2°C (mean 2.0°C) and 1.2–5.6°C (mean 3.1°C), respectively (Table 3.3). Precipitation was comparable between bands. Percent sand and gravel, as a measure of surficial geology and groundwater potential, was higher on average in the low band (39.8%) compared to the very-low band (26.4%). Forest cover was higher in the very-low band compared to the low band, with higher minimum, maximum, and mean values (45.9–83.1% with mean 64.8% compared to 29.5–63.8% with mean 43.8%, respectively; Table 3.3). Historical agriculture (1992) ranged from 1.9–31.6% across all 40 sites, compared to current agriculture (2011) that ranged from 0.0–20.4% across all sites. Open water and wetland both had higher average coverage in the watershed for sites in the low band compared to the very-low band (Table 3.3).

Dam density was comparable between very-low and low bands (Table 3.3). Longest undammed flow path had a higher maximum and higher mean value in the low band compared to very-low band, although the minimum lengths were comparable across bands. While the August altered flows ranged comparable values between each band, the ranges differed greatly between very-low and low bands for August percent difference (Table 3.3). In the very-low band, percent difference ranged from -100–18.0%, while in the low band the range was -95.6–579.3%. Negative values occur at depleted sites where unaltered flows are greater than altered flows; positive values occur at surcharged sites where altered flows are greater than unaltered flows. Altered flows were greater than unaltered flows at 5 sites in the very-low band compared to 10 sites in the low band. The value of 579.3% flow alteration represents an outlier at Monoosnuc Brook in Leominster, with much more water withdrawn relative to unaltered flows than at other sites. Monoosnuc Brook was also an outlier for August altered flows, as was the East Branch Housatonic River in Dalton.

Average road density was higher in the low band: 3.6 km/km^2 compared to 2.3 km/km^2 in the very-low band (Table 3.3). Although the total number of road-stream crossings in the watershed ranged considerably from 2–91 crossings (average 24 crossings in very-low band, 34 crossings in low band), once crossings were standardized to drainage area, the densities spanned similar ranges with similar means across very-low and low bands. Both flow length and gradient:length ratio exhibited higher minima, maxima, and means in the very-low band compared to the low band. One outlier was present for each metric: at Fall Brook in Freetown (very-low band) for gradient:length ratio and Monoosnuc Brook in Leominster (low band) for flow length.

3.3.4 Predictor-response relationships

The best-supported variables (i.e., ΔAICc = 0) within each predictor category of natural characteristics, land cover, flow alteration, and other urban measures differed across taxonomic groups, biotic response metrics, and by impervious band (Table 3.4, Figure 3.3, Appendix M). Combinations of predictor variables determined through all subsets modeling and variable importance similarly showed differences across taxa, metric, and band (Table 3.5, Figure 3.4, Appendix N). Minimum annual monthly minimum air temperature and open water were the predominant watershed-scale variables that both explained the most variance in biotic condition and were ranked highest for variable importance in multi-variable models of biotic responses. For example, minimum annual monthly minimum temperatures explained additional variance for both macroinvertebrates and fishes, particularly for in the very-low band for coldwater fishes (additional $R^2 = 0.42$) and macroinvertebrate tolerance (additional $R^2 = 0.40$).

3.3.4.1 Taxonomic group

Overall, fish assemblages were better explained by watershed-scale predictors than were macroinvertebrate assemblages. For macroinvertebrates, natural characteristics, other urban measures, and land cover contributed the most additional variance explained, after accounting for impervious cover. Fish assemblages were additionally explained by land cover and other urban measures, but also by flow alteration. The variables within each category also differed by taxonomic group. For land cover predictors, for instance, more historical agriculture was related to higher macroinvertebrate richness (additional $R^2 = 0.27$ in very-low band), while more watershed forest cover was related with more intolerant fishes (additional $R^2 = 0.40$ in very-low band). Housing density and impervious within the buffer most often explained the most biotic variance for the other urban predictor category: higher housing density was related to higher macroinvertebrate richness (additional $R^2 = 0.23$ in the low band) and more intolerant fishes (additional $R^2 = 0.20$ in the low band), while higher buffer impervious was related with greater fish richness (additional $R^2 = 0.12$ in low band) and more coldwater fishes (additional $R^2 = 0.18$ in low band). Flow alteration predictors (represented by dam density, August altered flows, and percent difference between August altered and unaltered flows) were more important for fish assemblages than macroinvertebrate assemblages.

3.3.4.2 Biotic response metric

Biotic response metrics differed in the amount of variance explained by watershed-scale predictors. For macroinvertebrates, tolerance and richness were best explained. By contrast, fluvial and thermal trait metrics for macroinvertebrates were not well explained: none of the watershed-scale predictors tested contributed $R^2 > 0.10$. For fish assemblages, the amount of variance explained also depended on which response metric was considered Watershed-scale factors explained the most additional variation for fluvial fishes (additional $R^2 = 0.22$ for both bands) and lesser amounts of variation for richness, coldwater, and tolerant fishes. Coldwater and intolerant fishes had similar amounts of variance explained, albeit by different watershed-scale predictors. Coldwater fishes were better explained by minimum annual monthly mean air temperature and impervious within the buffer, whereas intolerant fishes were better explained by open water, forest cover, and housing density.

3.3.4.3 Impervious band

The amount of variance explained, and which factors were most important, differed considerably based on which band—very low or low—was analyzed. In the very-low band, higher minimum annual monthly minimum air temperature was related with higher macroinvertebrate tolerance index (additional $R^2 = 0.46$), while in the low band, less precipitation was associated with higher tolerance (additional $R^2 = 0.20$). More historical agriculture contributed the most variance explained in addition to impervious in the very-low band (additional $R^2 = 0.27$) for macroinvertebrate richness, while higher housing density contributed additional $R^2 = 0.23$ in the low band. Overall, watershed-scale predictors explained more variance in the very-low band compared to the low band. Relative abundance of fluvial fishes was a notable exception, however: individual predictors from any predictor category added R^2 ranging 0.16–0.22 in the very-low band, whereas single predictors added R^2 ranging 0.15–0.81 in the low band. The predictor used in the flow alteration category—percent difference between August altered and unaltered flows—contributed $R^2 = 0.81$, in addition to the 0.02 explained by total impervious in the low band. The factors that contributed this additional variance differed by band, however: higher dam density for both bands, lower minimum annual monthly minimum air temperature in the very-low band, and higher August flow alteration in the low band.

3.4 Discussion

3.4.1 Watershed-scale variables explain differences in biotic condition

The importance of temperature in driving biotic assemblage structure was reinforced by this study. Minimum annual monthly minimum air temperature was the most frequently occurring watershed-scale predictor in equally plausible models and was often ranked as the most important variable among predictors in equally plausible models. However, air temperature was not strongly correlated with the suite of water temperature metrics calculated from direct measurement at the 40 stream sites in this study, a finding that has been documented in other studies (e.g., Booth et al. 2014), suggesting that something else related to air temperature may explain the responses. Minimum air temperatures were strongly correlated with land use measures (e.g., percent wetland) and elevation of both the watershed and the sampling site. This suggests that high-elevation streams are potentially more resistant to impacts of urbanization and have higher biotic integrity relative to lower elevation streams—particularly when integrity is measured by assemblages sensitive to flow, thermal, or water quality degradation. Other factors influence surface water temperatures in urban streams, however, such as riparian vegetation. For instance, urban sites that were shaded had cooler stream temperatures with less variance than urban sites exposed to open sun (Booth et al. 2014). Streams with steeper gradients and more catchment forest cover also had lower thermal sensitivity, which might allow greater stream ecosystem resilience to modest changes in land use (Hilderbrand et al. 2014).

Forest cover explained a substantial amount of variation in fish richness. Across the 40 study sites, total forest cover in the watershed and forest within the 120-m buffer upstream of the sampling site were highly correlated (r = 0.95); hence the use of forest in the watershed but not within the buffer as a predictor variable in biotic models. The importance of forest cover for maintaining high-quality fish assemblages has been demonstrated in numerous studies (Allan 2004, Lammert and Allan 1999). The beneficial role of riparian vegetation might be more important in watersheds with lower levels of urbanization (e.g., <15% urban land cover) than highly urbanized watersheds, at least for fish assemblages (Roy et al. 2007).

Macroinvertebrate richness was more highly explained by legacy agriculture cover in addition to impervious cover, rather than by forest or other current land cover types. Where urbanization occurs in historically agricultural watersheds, biota appear relatively unimpacted by urbanization, presumably because they have already experienced loss of sensitive species prior to urbanization (Cappiella et al. 2012), in contrast to urbanization in forested watersheds. Although current agricultural extent as of 2011 ranged from 0.0–20.4% for the 40 study watersheds, legacy agriculture based on a peak in 1992 ranged from 1.9–31.6%. As agricultural use declines in Massachusetts (Hall et al. 2002), formerly agricultural lands are often converted either to forest land or developed land (Hall et al. 2002), which often limits or reduces nutrient inputs in relation to past conditions (Utz et al. 2016). Thus, if macroinvertebrates become adapted to disturbance under agricultural conditions, they may be most able to resist future disturbances. This relates to other hypotheses about specific factors that might confer resistance to urbanization: that biota already adapted to naturally high conductivity and pH (Utz et al. 2016) or to naturally warmer stream temperatures (Hale et al. 2016) might be already adapted to cope with the types of thermal and water quality impairment associated with urbanization.

Open water was an important variable in models of macroinvertebrate richness, flow traits, and thermal traits, as well as intolerant fishes (Table 3.4). While open water was included in the land cover category, it was correlated with dam density (r = 0.67), which was used in the flow alteration predictor category. In several instances, both open water and dam density were represented as the best predictors from their respective predictor categories. When used in flow-trait models, however, the tested predictor–

response relationships ran counter to expectations. In particular, higher relative abundance of fluvial fishes was explained in equally plausible models by higher dam density (both bands, very-low band). The positive relationship between dam density and fluvial fishes is potentially an artifact of more dams being located in high-gradient watersheds where more riffle habitat already exists conducive to fluvial fish abundance. Although elevation, reach slope, and dam density were not highly correlated ($r < 0.50$) in this study, watershed slope was not tested and might be a better predictor of dam siting than local reach slope.

Where they do exist on the landscape, dams and impoundments affect flow, temperature, and sediment regimes, with subsequent effects on stream geomorphology and physical habitat features (Ligon et al. 1995); these effects may occur prior or concomitant with impervious cover development. Dams are prevalent in the Northeast, with many current and historical dams covering many Massachusetts waterways. Although water retained in dams and impoundments alters the hydrological regime, the increased water storage might mitigate impervious-induced hydrological changes, particularly with regard to flashiness. Indeed, one characteristic of streams potentially better suited to resist the effects of urbanization is greater water storage capacity (Utz et al. 2016) such as provided by wetlands or impoundments (Hopkins et al. 2015). Hence, the relationship between open water and dams, as well as their implications for biota, in the context of urbanization requires further investigation.

Higher relative abundance of fluvial fishes was also explained by higher flow alteration. The August flow alteration metric (percent difference between altered and unaltered flows) incorporates both withdrawals (negative values) and return flows (positive values) from a variety of sources: withdrawals from groundwater, surface water, direct river intake, and domestic wells, and return flows from groundwater, surface water, and domestic septic. Two sites in particular had highly positive flow alteration values, both in the low band, which potentially drove the relationship observed in the low band but not in the very-low band. Armstrong et al. (2011) found fewer fluvial fishes with more August flow alterations, although this only included depleted sites, not surcharged sites receiving wastewater discharges. Kanno and Vokoun (2010) also demonstrated that higher water withdrawal rates were related to proportionally fewer fluvial dependents.

Contrary to other studies demonstrating the influence of directly connected impervious, road networks, or spatial arrangement of impervious cover (Walsh et al. 2005), this study did not provide strong evidence for other measures of urbanization or impervious that explained biotic assemblages better than total impervious cover. Of the eight predictors within the “other urban measures” predictor category, all appeared at least once as the best predictor of the category. However, other urban measures only contributed additional variance (albeit, additional $R^2 < 0.25$) more than predictors in other categories in a few instances: in the very-low band, more road crossings best explained coldwater macroinvertebrates, while in the low band, higher housing density best explained macroinvertebrate richness and intolerant fishes, and higher impervious in the buffer best explained fish richness and coldwater fishes. The more frequent occurrence and greater additional variance explained for other urban measures in the low band might indicate that those streams have already been subjected to the detrimental effects of impervious cover, while the very-low band is still influenced more by other factors in the watershed.

Part of why other measures of impervious did not emerge as more important might be attributed to imperfect methods of assessment. While road density has been shown to be an important metric to quantify the effects of the transportation network on ecology, finer-tuned measures of the road network might contribute additional explanation of variance, such as road width, type, traffic density, road connectivity, and network structure (Forman and Alexander 1998, Jones et al. 2000). For example, roads with curbs often have stormwater drains connecting directly to streams, providing a higher impact of storm flows and contaminants on streams compared to roads with vegetated swales. The importance of impervious within a 120-m buffer of the stream channel requires further investigation, as impervious located within proximity to stream channels is often part of the road network, particularly in more mountainous areas (Forman and Alexander 1998) where roads and streams parallel but do not necessarily intersect, as would be detected by the road-stream crossings metric. In Massachusetts, Forman and Deblinger (2000) estimated that ecological effects from roads, including stream channelization, wetland drainage, and road salt, extended at least 100 m but also beyond 1 km from the road.

Furthermore, total road crossings were more important and explained more variance than road-crossing density. Total road crossings exhibited more variability (i.e., coefficient of variation) in very-low and low bands than road-crossing density (Table 3.3). Use of total road crossings potentially indicates cumulative effects within a stream network, particularly since the location of crossings may be where most runoff enters stream channels. The directionality of the relationship was contrary to expectations, however: higher abundance of fluvial fishes was related to more road crossings. This could be indicative of several issues, with potentially different mechanisms: while fluvial fishes require flowing water for most or all of their life cycle, some fluvial fishes (e.g., slimy sculpin) are highly sensitive to thermal and water quality conditions, whereas other fluvial fishes (e.g., white sucker) are more tolerant of degraded conditions such as warmer water or lower dissolved oxygen. Road crossings can also act as barriers that fragment the aquatic connectivity and isolate biotic populations, which is often related to the type of crossing. Although specific characteristics of road crossings were not assessed in this study, biota are differentially affected by the type of crossing: bridges typically allow better passage of materials (e.g. flows, debris), including stream biota, than do culverts, particularly when culverts are undersized or perched (Forman and Alexander 1998, MA DER 2012). Fluvial fishes vary in their movement within streams: some are more confined to localized riffle habitats, whereas others exhibit greater movement within the stream network.

3.4.2 Fish and macroinvertebrate responses differ

Across the four types of biotic response metrics—richness, flow traits, thermal traits, and tolerance—fish assemblages were overall better explained by watershed-scale factors than were macroinvertebrate assemblages. Brown et al. (2009) attributed the generally weak correlations of fish assemblages to urbanization to historical land use, especially agricultural use, instigating fish community changes prior to urbanization. In contrast, results from the NAWQA assessments in urban streams found that macroinvertebrates were better related to urban landscape metrics (e.g., housing density, percent developed land, road density) than fishes. Walters et al. (2009) also found that macroinvertebrates were more sensitive than fishes to environmental changes at low levels of urbanization. Some of the lowest biotic thresholds to impervious cover have been documented for sensitive macroinvertebrates, which have been shown to decline at very low (0.5–2.0%) levels of watershed impervious cover (King et al. 2011). The urban stream syndrome tends to show more consistent declines for macroinvertebrates than fishes (Walsh et al. 2005). These documented declines in macroinvertebrates are based on studies along a gradient of increasing urbanization or impervious cover. At the low levels of impervious cover at which this study focused, it is possible that macroinvertebrates were already degraded and therefore the range of variability was already suppressed, more so than for fishes, which still retained sufficient variability to be explained by the watershed-scale factors tested.

3.4.3 Responses vary based on the biotic metric used

Tolerance and richness were best explained for macroinvertebrates. Macroinvertebrate richness was associated with higher historical agriculture and higher housing density, likely because more taxa have intermediate tolerance levels than are intolerant. Tolerance, however, was determined mainly by temperature metrics, reflecting thermal pollution as a stronger stressor than other stressors manifested at the watershed scale (e.g., dams, flow alteration). By contrast, fluvial and thermal trait metrics for macroinvertebrates were not well explained. The same issues that plagued macroinvertebrate flow and thermal trait metrics for reach-scale variables also apply for watershed-scale variables.

For fish assemblages, the amount of variance explained also depended on which response metric was considered. Watershed-scale factors explained the most additional variation for fluvial fishes and lesser amounts of variation for richness, coldwater, and tolerant fishes. Fluvial fish richness and relative abundance were also highly correlated and explained by watershed-scale factors in Armstrong et al. (2011). Coldwater fish relative abundance was predominated by fallfish and brook trout, however, fallfish should likely be classified as cool-warmwater instead, which affected the variables that best explained this metric: although more coldwater fishes were related with colder minimum annual monthly mean air temperature, they were also related with more impervious within the buffer. Intolerant fishes, predominantly comprised of brook trout, were better explained by measures of land cover (e.g., open water, forest cover) and housing density. Given the sensitivity of brook trout to thermal alteration (Eaton et al. 1995, Taniguchi et al. 1998, Wehrly et al. 2003), it is surprisingly that temperature metrics did not contribute more additional variance in relation to the other types of predictors tested (i.e., land use, flow alteration, other urban measures).

3.4.4 Reponses vary based on impervious cover band

The differences in responses to predictors between very-low and low bands potentially demonstrate how impacts of urbanization are manifested at low levels of urbanization. This is particularly evident for fishes, where watershed-scale factors explain much more additional variance for fluvial fishes in the low band compared to the very-low band. Because the low band spans a range (6.7–10.0%) in impervious that is near where we would expect considerable decline in biotic integrity, it is possible that the high explanatory power is linked to imperious-induced flow alteration. The striking difference for fluvial fishes between bands highlights the role of August flow alteration and modeled flow length (weight 2.0) for sites in the low band. In contrast to fluvial fishes, more additional variance for coldwater and intolerant fishes was explained in the very-low band compared to the low band, suggesting that these fishes are sensitive to watershed-scale disturbances even at very low levels of impervious cover. The amount of variance explained for fish richness is similar across bands, but in the very-low band this is mostly accounted for by watershed-scale factors, whereas in the low band most variance is explained by total impervious.

3.4.5 Conclusion

Biotic assemblages showed wide variability in streams with low-levels of urbanization (<10% impervious cover) in this study. Watershed-scale factors, encompassing natural characteristics, land cover, flow alteration, and other measures of urbanization, accounted for additional variance in explaining biotic condition than total impervious cover alone. In particular, sites with lower minimum air temperature, which was highly correlated with high-elevation areas, retained high biotic integrity as measured by higher relative abundances of fluvial, coldwater, and intolerant taxa. Furthermore, these higher quality biotic conditions were present in high-elevation areas despite other stressors, such as dams, flow alteration, and road crossings. As such, we suggest prioritizing watersheds in these high-elevation cold regions for protection while working to reduce existing stressors (e.g., dams, road crossings).

Table 3.1. Watershed-scale variables for each of the predictor categories representing natural characteristics, land cover, flow alteration, and other urban measures. Descriptions of each variable are given, as well as the relevant units, data resolution (i.e., pixel size), and the relevant years from which data were acquired. NLCD = National Land Cover Database; PRISM = Parameter-elevation Relationships on Independent Slopes Model

Group	Predictor	Units	Resolution	Years	Description	Data source(s)
Natural characteristics						
	Drainage area	km2			Contributing area draining to sampling site	
	Elevation, basin	m			Mean elevation of drainage area	
	Elevation, site	m			Elevation of sampling site	
	Sand and gravel	%			Sand and gravel in the drainage area	
	Precipitation, mean	mm		1971-2000	Mean precipitation	PRISM
	Max annual monthly max temp	°C		1971-2000	Maximum of monthly annual maximum air temperature	PRISM
	Mean annual monthly max temp	°C		1971-2000	Mean of monthly annual maximum air temperature	PRISM
	Min annual monthly min temp	°C		1971-2000	Minimum of monthly annual minimum air temperature	PRISM
	Mean annual monthly min temp	°C		1971-2000	Mean of monthly annual minimum air temperature	PRISM
Land cover						
	Open Water, 2011; Open Water, 2006	%	30-m	2011, 2006	Areas of open water, generally with less than 25% cover of vegetation or soil; percent of contributing area	NLCD
	Developed, 2011; Developed, 2006	%	30-m	2011, 2006	Aggregation of Open Space Developed, Low Intensity Developed, Medium Intensity Developed, and High Intensity Developed classifications; percent of contributing area	NLCD
	Forest, 2011; Forest, 2006	%	30-m	2011, 2006	Aggregation of Deciduous Forest, Evergreen Forest, and Mixed Forest classifications; percent of contributing area	NLCD
	Agriculture, 2011; Agriculture, 2006	%	30-m	2011, 2006	Aggregation of Pasture/Hay and Cultivated Crops classifications; percent of contributing area	NLCD
	Wetland, 2011; Wetland, 2006	%	30-m	2011, 2006	Aggregation of Woody Wetlands and Emergent Herbaceous Wetlands classifications; percent of contributing area	NLCD
	Open Water, buffer, 2011	%	30-m	2011	Areas of open water, generally with less than 25% cover of vegetation or soil; percent of 120-m width buffer upstream of sampling site	NLCD
	Developed, buffer, 2011	%	30-m	2011	Aggregation of Open Space Developed, Low Intensity Developed, Medium Intensity Developed, and High Intensity Developed classifications; percent of 120-m width buffer upstream of sampling site	NLCD
	Forest, buffer, 2011	%	30-m	2011	Aggregation of Deciduous Forest, Evergreen Forest, and Mixed Forest classifications; percent of 120-m width buffer upstream of sampling site	NLCD
	Agriculture, buffer, 2011	%	30-m	2011	Aggregation of Pasture/Hay and Cultivated Crops classifications; percent of 120-m width buffer upstream of sampling site	NLCD
	Wetland, buffer, 2011	%	30-m	2011	Aggregation of Woody Wetlands and Emergent Herbaceous Wetlands classifications; percent of 120-m width buffer upstream of sampling site	NLCD
	Agriculture, 1992	%	30-m	1992	Aggregation of Pasture/Hay, Row Crops, Small Grains, and Fallow classifications; percent of contributing area	NLCD

Table 3.1, continued

Group	Predictor	Units	Resolution	Years	Description	Data source(s)
Flow alteration						
	Dams, total	dams			Number of dams in contributing area	MassGIS; Massachusetts Office of Dam Safety
	Dams, per drainage area	dams/km2			Number of dams per contributing area	
	Dams, per stream length	dams/km2			Number of dams per stream length in contributing area	
	Longest undammed flow path				Length of undammed stream channel along longest flow path both upstream and downstream of sampling site	
	Dams, upstream YN				Presence or absence of dams in contributing area	
	Flow unaltered, Jun	m3/s		2010-2014	Median monthly unaltered streamflow, June	Sustainable Yield Estimator; Archfield et al. 2010
	Flow unaltered, Jul	m3/s		2010-2014	Median monthly unaltered streamflow, July	
	Flow unaltered, Aug	m3/s		2010-2014	Median monthly unaltered streamflow, August	
	Flow unaltered, Sep	m3/s		2010-2014	Median monthly unaltered streamflow, September	
	Flow altered, Jun	m3/s		2010-2014	Median monthly altered streamflow, June	
	Flow altered, Jul	m3/s		2010-2014	Median monthly altered streamflow, July	
	Flow altered, Aug	m3/s		2010-2014	Median monthly altered streamflow, August	
	Flow altered, Sep	m3/s		2010-2014	Median monthly altered streamflow, September	
	Flow percent dif, Jun	%		2010-2014	Percent difference between median monthly altered and unaltered streamflows, June	
	Flow percent dif, Jul	%		2010-2014	Percent difference between median monthly altered and unaltered streamflows, July	
	Flow percent dif, Aug	%		2010-2014	Percent difference between median monthly altered and unaltered streamflows, August	
	Flow percent dif, Sep	%		2010-2014	Percent difference between median monthly altered and unaltered streamflows, September	
	Flow percent dif, mean	%		2010-2014	Percent difference between median monthly altered and unaltered streamflows, annual mean	
Other urban						
	Impervious, 2006 NLCD	%	30-m	2006	Percent impervious cover in the contributing area; each pixel assigned value 0-100	NLCD 2006
	Impervious, 2006 to 2011 dif	%	30-m	2011, 2006	Difference between 2011 and 2006 percent impervous cover in the contributing area	NLCD 2011, NLCD 2006
	Impervious, 2005 MassGIS	%	1-m	2005	Percent impervious cover in the contributing area; each pixel assigned binary 0 or 1	MassGIS
	Impervious, buffer, 10m	%	10-m			NLCD 2011, MassGIS
	Impervious, buffer, 2011 NLCD	%	30-m	2011		NLCD 2011
	Population density	people/km2			Number of people per contributing area	
	Housing density	houses/km2			Number of houses per contributing area	
	Road density	km/km2			Road length per contributing area	
	Road crossings, total	crossings			Number of road-stream crossings in contributing area	
	Road crossings, density	crossings/km2			Number of road-stream crossings per contributing area	
	Flow length, wgt 0.5				Relative flow length distance along surface pathway to sampling site; higher weights place greater emphasis on proximate locations	Matt Baker (UMBC) and Lance Ostiguy (USGS)
	Flow length, wgt 1.0					
	Flow length, wgt 1.5					
	Flow length, wgt 2.0					
	Gradient:length ratio, wgt 0.5				Relation of flow gradient to flow length; used as a topographic estimate of water residence time; higher weights place greater emphasis on proximate locations	Matt Baker (UMBC) and Lance Ostiguy (USGS)
	Gradient:length ratio, wgt 1.0					
	Gradient:length ratio, wgt 1.5					
	Gradient:length ratio, wgt 2.0					

Table 3.2. Summary statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) for biotic response variables, grouped by response variable category and impervious cover band (very low = 1–4%, low = 7–10%) at 40 sites across Massachusetts, sampled during 2005–2015.

Response group	Very-low band					Low band				
Response variable	Min	Max	Mean	SD	CV	Min	Max	Mean	SD	CV
Richness										
Macroinvertebrate taxa richness	12.0	41.2	28.7	6.99	0.24	8.9	42.0	25.0	7.86	0.31
Fish species richness	3.0	10.0	6.4	2.09	0.33	2.0	9.0	5.0	2.36	0.47
Flow traits										
Macroinvertebrate flow traits, rel abund (%)	24.7	84.0	51.0	18.21	0.36	13.5	96.1	50.7	27.94	0.55
Fish, fluvial rel abund (%)	10.5	100.0	71.2	33.72	0.47	0.0	100.0	38.8	41.50	1.07
Thermal traits										
Macroinvertebrates, coldwater rel abund (%)	5.0	59.0	31.4	16.79	0.53	1.0	62.9	22.9	16.13	0.70
Fish, coldwater rel abund (%)	0.0	96.1	33.9	32.77	0.97	0.0	60.6	10.1	16.62	1.65
Tolerance										
Macroinvertebrate tolerance index	3.4	7.2	5.0	0.98	0.20	3.6	7.7	5.3	0.92	0.18
Fish, intolerant rel abund (%)	0.0	96.1	18.2	29.25	1.61	0.0	50.0	8.1	14.92	1.85

Table 3.3. Summary statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) for variables within each predictor category, by impervious cover band (very low = 1–4%, low = 7–10%) at 40 sites across Massachusetts.

			Very-low band					Low band				
Category	Predictor variable	Units	Min	Max	Mean	SD	CV	Min	Max	Mean	SD	CV
Natural characteristics												
	Drainage area	km2	5.8	72.1	21.3	17.44	0.82	5.3	66.3	23.4	17.40	0.74
	Sand and gravel	%	0.0	73.0	26.4	19.59	0.74	5.0	79.8	39.8	24.39	0.61
	Precipitation, mean	mm	1174.7	1296.1	1230.5	32.69	0.03	1173.4	1253.3	1222.0	23.49	0.02
	Max annual monthly max temp	°C	12.9	15.6	14.4	0.86	0.06	14.2	15.9	15.3	0.41	0.03
	Min annual monthly min temp	°C	-0.2	5.2	2.0	1.47	0.74	1.2	5.6	3.1	1.05	0.33
Land cover												
	Open Water, 2011	%	0.0	6.7	1.8	1.96	1.07	0.0	13.8	2.4	3.27	1.38
	Forest, 2011	%	45.9	83.1	64.8	9.42	0.15	29.5	63.8	43.8	8.49	0.19
	Agriculture, 2011	%	0.3	15.8	6.6	4.49	0.68	0.0	20.4	6.3	5.53	0.88
	Wetland, 2011	%	1.3	39.4	13.7	8.60	0.63	5.8	28.9	16.5	5.70	0.35
	Agriculture, 1992	%	2.2	21.8	9.8	5.35	0.55	1.9	31.6	11.2	7.86	0.70
Flow alteration												
	Dams, per drainage area	dams/km2	0.0	3.1	0.9	0.82	0.90	0.0	3.2	1.0	0.89	0.92
	Longest undammed flow path	km	1.1	32.8	11.1	7.86	0.71	1.3	38.9	13.6	9.37	0.69
	Flow altered, Aug	m3/s	0.00	0.25	0.05	0.06	1.27	0.00	0.50	0.08	0.11	1.43
	Flow percent dif, Aug		-100.0	18.0	-21.8	35.33	-1.62	-95.6	579.3	20.8	137.40	6.62
Other urban												
	Impervious, 2006 to 2011 dif	%	0.0	0.4	0.1	0.10	1.22	0.0	1.7	0.5	0.44	0.87
	Impervious, buffer, 10m-res	%	1.9	8.1	4.3	1.30	0.30	4.5	9.9	7.4	1.56	0.21
	Housing density	houses/km2	9.2	148.8	49.1	30.24	0.62	40.1	125.6	64.9	21.45	0.33
	Road density	km/km2	1.1	3.6	2.3	0.76	0.33	2.7	4.5	3.6	0.48	0.13
	Road crossings, total	crossings	2.0	86.0	23.9	21.66	0.91	8.0	91.0	33.5	23.67	0.71
	Road crossings, density	crossings/km2	0.3	3.2	1.2	0.69	0.59	0.8	3.0	1.5	0.53	0.35
	Flow length, wgt 2.0		0.9	15.8	5.5	4.20	0.77	3.1	61.2	13.3	12.98	0.97
	Gradient:length ratio, wgt 2.0		0.0	58.4	5.6	12.96	2.32	0.0	81.0	14.6	25.86	1.77

Table 3.4 Predictors with the lowest AICc from model selection within each watershed-scale predictor category (Appendix M) are shown with the directionality (estimate) and variance explained (R^2) for impervious (IC) and the additional predictor (pred) in each biotic response model. Models were run for: both bands (*n* = 40), very-low band (1–4%, *n* = 20), and low band (7–10%, *n* = 20).

Response group	Both bands					Very-low band					Low band				
Response metric		Estimate					Estimate					Estimate			
Predictor category	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2
Richness															
Macroinvertebrate taxa richness															
	Impervious	-		0.10		Impervious	-		0.02		Impervious	-		0.12	
Natural characteristics	Sand and gravel	-	-	0.14	0.05	Sand and gravel	-	-	0.18	0.16	Sand and gravel	-	-	0.14	0.02
Land cover	**Agriculture, 1992**	**-**	**+**	**0.18**	**0.08**	**Agriculture, 1992**	**-**	**+**	**0.29**	**0.27**	Open Water, 2011	-	-	0.22	0.10
Flow alteration	Flow altered, Aug	-	+	0.14	0.04	Flow altered, Aug	+	+	0.16	0.14	Flow altered, Aug	-	+	0.16	0.04
Other urban	Impervious, buffer, 10m-res	-	+	0.17	0.08	Housing density	-	-	0.25	0.23	**Housing density**	**-**	**+**	**0.35**	**0.23**
Fish species richness															
	Impervious	-		0.13		Impervious	-		0.00		Impervious	-		0.18	
Natural characteristics	**Drainage area**	**-**	**+**	**0.22**	**0.10**	Max annual monthly max temp	+	-	0.17	0.16	Min annual monthly min temp	-	-	0.29	0.10
Land cover	Forest, 2011	-	-	0.20	0.07	Agriculture, 2011	-	+	0.11	0.10	Forest, 2011	-	-	0.26	0.07
Flow alteration	Longest undammed flow path	-	-	0.14	0.02	**Flow altered, Aug**	**+**	**+**	**0.24**	**0.24**	Longest undammed flow path	-	-	0.23	0.05
Other urban	Road crossings, total	-	+	0.18	0.05	Gradient:length ratio, wgt 2.0	-	-	0.08	0.08	**Impervious, buffer, 10m-res**	**-**	**+**	**0.31**	**0.12**
Flow traits															
Macroinvertebrate flow traits, rel abund (%)															
	Impervious	+		0.00		Impervious	+		0.01		Impervious	+		0.02	
Natural characteristics	Sand and gravel	+	+	0.01	0.00	**Min annual monthly min temp**	**+**	**+**	**0.04**	**0.03**	Min annual monthly min temp	+	-	0.07	0.04
Land cover	**Open Water, 2011**	**+**	**+**	**0.05**	**0.04**	Wetland, 2011	+	+	0.03	0.02	**Open Water, 2011**	**+**	**+**	**0.11**	**0.08**
Flow alteration	Dams, per drainage area	+	+	0.03	0.03	Dams, per drainage area	+	+	0.01	0.00	Dams, per drainage area	+	+	0.08	0.06
Other urban	Impervious, 2006 to 2011 dif	-	+	0.02	0.01	Housing density	+	+	0.02	0.01	Housing density	+	-	0.07	0.05
Fish, fluvial rel abund (%)															
	Impervious	-		0.16		Impervious	-		0.00		Impervious	-		0.01	
Natural characteristics	Min annual monthly min temp	-	-	0.35	0.19	**Min annual monthly min temp**	**+**	**-**	**0.22**	**0.22**	Min annual monthly min temp	-	-	0.36	0.35
Land cover	Wetland, 2011	-	-	0.26	0.10	Wetland, 2011	+	-	0.18	0.17	Wetland, 2011	-	-	0.16	0.15
Flow alteration	**Dams, per drainage area**	**-**	**+**	**0.38**	**0.22**	Dams, per drainage area	-	+	0.17	0.16	**Flow percent dif, Aug**	**-**	**+**	**0.82**	**0.81**
Other urban	Flow length, wgt 2.0	-	+	0.36	0.20	Road crossings, density	-	+	0.16	0.15	Flow length, wgt 2.0	-	+	0.47	0.45

Table 3.4, continued

Response group	Both bands					Very-low band					Low band				
Response metric		Estimate					Estimate					Estimate			
Predictor category	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2	Predictor	IC	Pred	R2	Add R2
Thermal traits															
Macroinvertebrates, coldwater rel abund (%)															
	Impervious	-		0.03		Impervious	-		0.03		Impervious	-		0.00	
Natural characteristics	Drainage area	-	-	0.05	0.02	Sand and gravel	-	+	0.08	0.05	Drainage area	-	-	0.03	0.03
Land cover	**Open Water, 2011**	**-**	**-**	**0.09**	**0.07**	Open Water, 2011	-	-	0.08	0.05	**Open Water, 2011**	**+**	**-**	**0.10**	**0.09**
Flow alteration	Dams, per drainage area	-	-	0.07	0.04	Dams, per drainage area	-	-	0.07	0.03	Dams, per drainage area	+	-	0.03	0.03
Other urban	Road crossings, total	-	-	0.07	0.04	**Road crossings, total**	**-**	**-**	**0.09**	**0.06**	Road density	-	+	0.03	0.03
Fish, coldwater rel abund (%)															
	Impervious	-		0.14		Impervious	+		0.00		Impervious	-		0.12	
Natural characteristics	**Min annual monthly min temp**	**-**	**-**	**0.30**	**0.15**	**Min annual monthly min temp**	**+**	**-**	**0.42**	**0.42**	Min annual monthly min temp	-	-	0.22	0.11
Land cover	Wetland, 2011	-	-	0.19	0.05	Forest, 2011	+	+	0.37	0.36	Agriculture, 1992	-	+	0.20	0.08
Flow alteration	Dams, per drainage area	-	+	0.19	0.04	Flow percent dif, Aug	+	-	0.14	0.13	Longest undammed flow path	-	-	0.20	0.08
Other urban	Impervious, buffer, 10m-res	-	+	0.22	0.08	Gradient:length ratio, wgt 2.0	+	-	0.30	0.29	**Impervious, buffer, 10m-res**	**-**	**+**	**0.30**	**0.18**
Tolerance															
Macroinvertebrate tolerance index															
	Impervious	+		0.06		Impervious	+		0.15		Impervious	+		0.08	
Natural characteristics	**Min annual monthly min temp**	**+**	**+**	**0.26**	**0.19**	**Min annual monthly min temp**	**+**	**+**	**0.61**	**0.46**	**Precipitation, mean**	**+**	**-**	**0.28**	**0.20**
Land cover	Forest, 2011	-	-	0.19	0.12	Wetland, 2011	+	+	0.29	0.14	Forest, 2011	+	-	0.22	0.14
Flow alteration	Longest undammed flow path	+	+	0.09	0.03	Flow percent dif, Aug	+	+	0.19	0.04	Longest undammed flow path	+	+	0.11	0.03
Other urban	Impervious, buffer, 10m-res	+	-	0.11	0.04	Gradient:length ratio, wgt 2.0	+	+	0.44	0.30	Impervious, buffer, 10m-res	+	-	0.19	0.11
Fish, intolerant rel abund (%)															
	Impervious	-		0.05		Impervious	-		0.14		Impervious	-		0.01	
Natural characteristics	Min annual monthly min temp	-	-	0.12	0.07	Precipitation, mean	-	-	0.28	0.14	Max annual monthly max temp	-	-	0.16	0.15
Land cover	**Open Water, 2011**	**-**	**-**	**0.20**	**0.15**	**Forest, 2011**	**+**	**+**	**0.55**	**0.40**	Wetland, 2011	-	+	0.09	0.08
Flow alteration	Dams, per drainage area	-	-	0.13	0.08	Dams, per drainage area	-	-	0.28	0.14	Flow altered, Aug	-	-	0.20	0.19
Other urban	Road crossings, total	-	-	0.18	0.13	Flow length, wgt 2.0	-	-	0.33	0.19	**Housing density**	**+**	**+**	**0.21**	**0.20**

Note: Variables with the highest R^2 for each biotic response metric in each band are highlighted in bold.

Table 3.5. Variable importance was determined through all-subsets GLMs and GLMMs for each biotic response metric. The all-subsets approach ran models for every variable combination of impervious cover and the top-performing predictor from each predictor category of natural characteristics, land cover, flow alteration, and other urban measures. Model weights (*w*) were calculated based on corrected Aikaike Information Criterion (AICc) values across all 31 models run. Variable importance was calculated for equally plausible models (< 2 ΔAICc); Σ*w* represents the sum of model weights for each model in which the variable appeared. Higher Σ*w* values indicate more important variables. Impervious cover is highlighted in gray.

	Both bands		Very-low band		Low band	
Response	Predictor	Σ*w*	Predictor	Σ*w*	Predictor	Σ*w*
Richness						
Macroinvertebrate taxa richness						
	Impervious	0.59	Impervious	0.34	Sand and gravel	0.21
	Agriculture, 1992	0.46	Agriculture, 1992	0.23	Open Water, 2011	0.09
	Impervious, buffer, 10m-res	0.36				
	Flow altered, Aug	0.16				
	Sand and gravel	0.15				
Fish species richness						
	Impervious	0.47	Flow altered, Aug	0.31	Impervious	0.45
	Drainage area	0.26	Agriculture, 2011	0.15	Impervious, buffer, 10m-res	0.25
	Forest, 2011	0.20	Gradient:length ratio, wgt 2.0	0.12	Longest undammed flow path	0.20
	Road crossings, total	0.06	Max annual monthly max temp	0.10	Min annual monthly min temp	0.12
					Forest, 2011	0.11
Flow traits						
Macroinvertebrate flow traits, rel abund (%)						
	Open Water, 2011	0.47	Min annual monthly min temp	0.26	Open Water, 2011	0.46
	Impervious, 2006 to 2011 dif	0.35			Housing density	0.28
	Impervious	0.09			Min annual monthly min temp	0.21
	Dams, per drainage area	0.07			Dams, per drainage area	0.12
Fish, fluvial rel abund (%)						
	Impervious	0.62	Min annual monthly min temp	0.53	Min annual monthly min temp	0.52
	Min annual monthly min temp	0.62	Dams, per drainage area	0.35	Flow percent dif, Aug	0.52
	Dams, per drainage area	0.62	Road crossings, density	0.29	Impervious	0.22
	Flow length, wgt 2.0	0.62				
	Wetland, 2011	0.21				
Thermal traits						
Macroinvertebrates, coldwater rel abund (%)						
	Open Water, 2011	0.48	Impervious	0.37	Open Water, 2011	0.60
	Road crossings, total	0.48	Road crossings, total	0.33	Road density	0.60
	Impervious	0.19	Dams, per drainage area	0.27	Drainage area	0.19
	Drainage area	0.12				
Fish, coldwater rel abund (%)						
	Min annual monthly min temp	0.42	Impervious	0.40	Impervious, buffer, 10m-res	0.39
	Impervious	0.13	Forest, 2011	0.31	Longest undammed flow path	0.34
			Gradient:length ratio, wgt 2.0	0.31	Impervious	0.30
			Min annual monthly min temp	0.19	Agriculture, 1992	0.19
			Flow percent dif, Aug	0.18	Min annual monthly min temp	0.15
Tolerance						
Macroinvertebrate tolerance index						
	Min annual monthly min temp	0.48	Min annual monthly min temp	0.64	Precipitation, mean	0.23
	Longest undammed flow path	0.27	Gradient:length ratio, wgt 2.0	0.29	Impervious	0.23
	Forest, 2011	0.16	Impervious	0.26	Forest, 2011	0.17
					Impervious, buffer, 10m-res	0.12
					Longest undammed flow path	0.11
Fish, intolerant rel abund (%)						
	Min annual monthly min temp	0.67	Forest, 2011	0.45	Housing density	0.42
	Road crossings, total	0.42	Flow length, wgt 2.0	0.45	Max annual monthly max temp	0.11
	Dams, per drainage area	0.33	Dams, per drainage area	0.16	Flow altered, Aug	0.09
	Open Water, 2011	0.33				

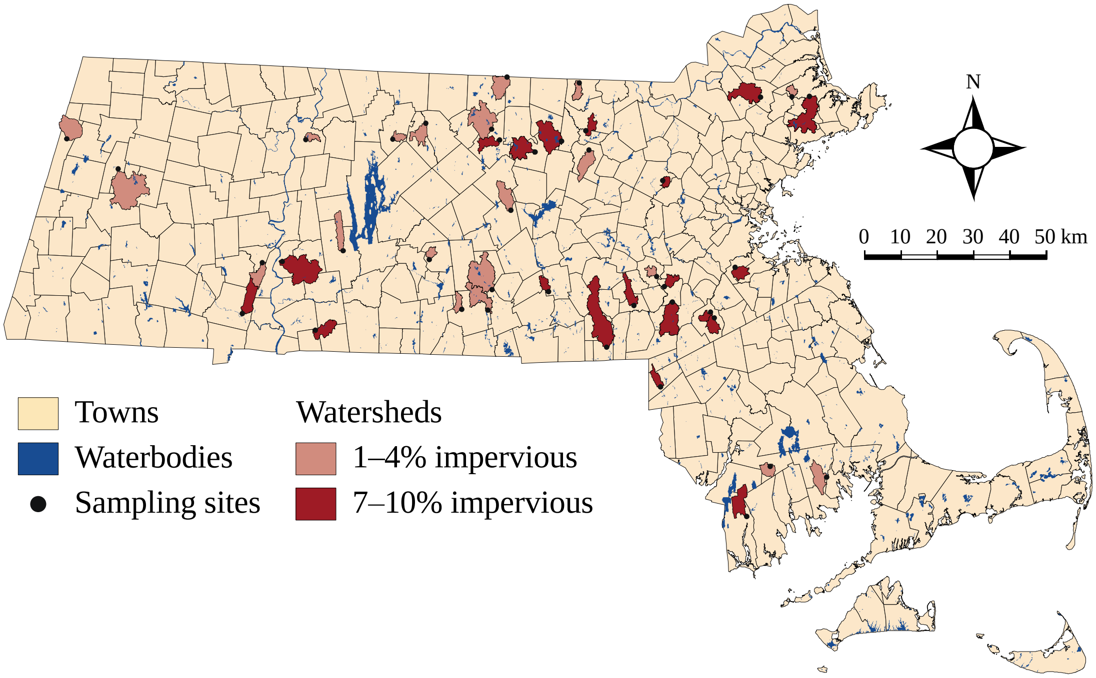


Figure 3.1. Forty sites sampled across Massachusetts within two bands of impervious cover: 1–4% (*n* = 20; pink) and 7–10% (*n* = 20; red) during 2014–2016. Major waterbodies (large rivers, lakes; blue) and town boundaries are also shown.

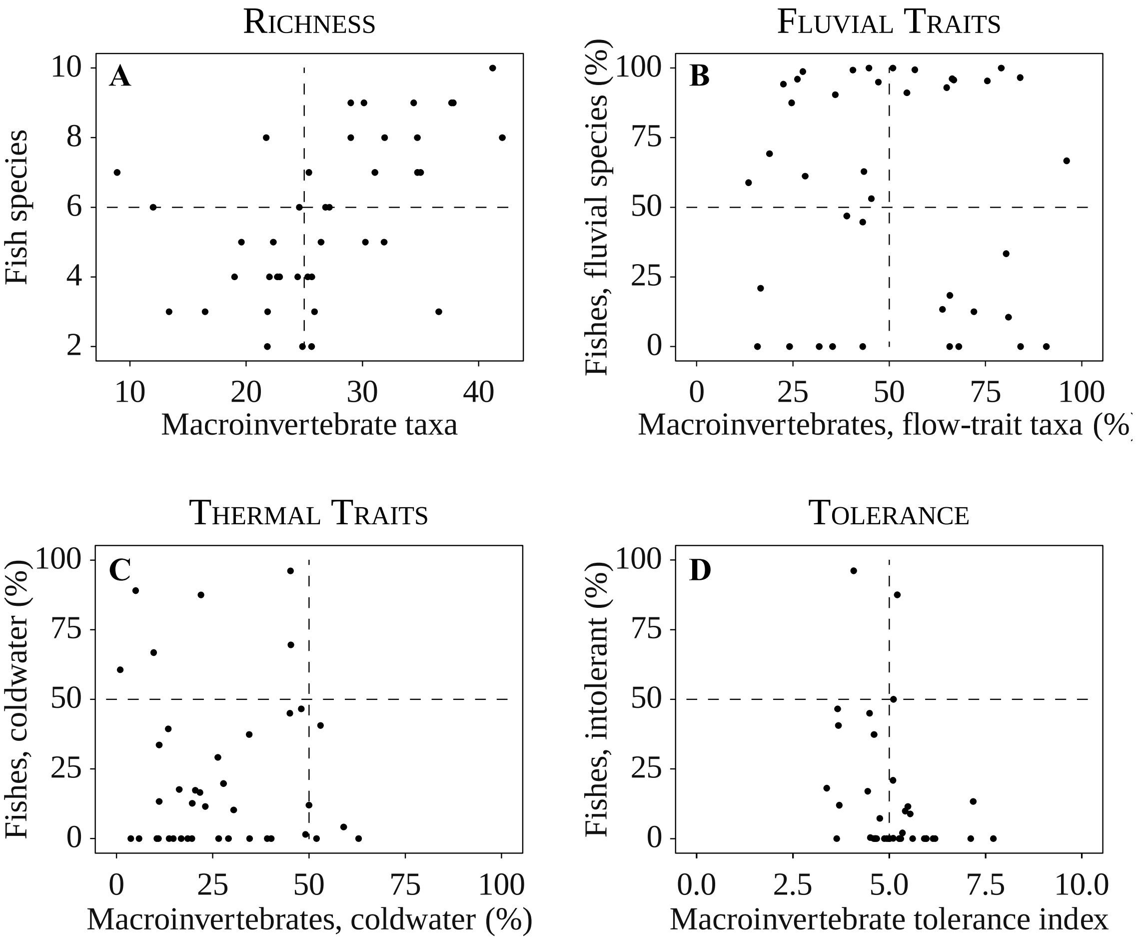


Figure 3.2. Scatterplots of biotic responses comparing similar metrics for each taxonomic group. Macroinvertebrates are shown on the x-axis and fishes are displayed on the y-axis. The metrics compared include richness (A), fluvial traits (B), thermal traits (C), and tolerance (D). Dotted lines divide each graph into four quadrants based on better or worse condition. Good condition for both macroinvertebrates and fishes at the same site is represented within the upper right quadrant for richness, fluvial traits, and thermal traits, and within the upper left quadrant for tolerance.

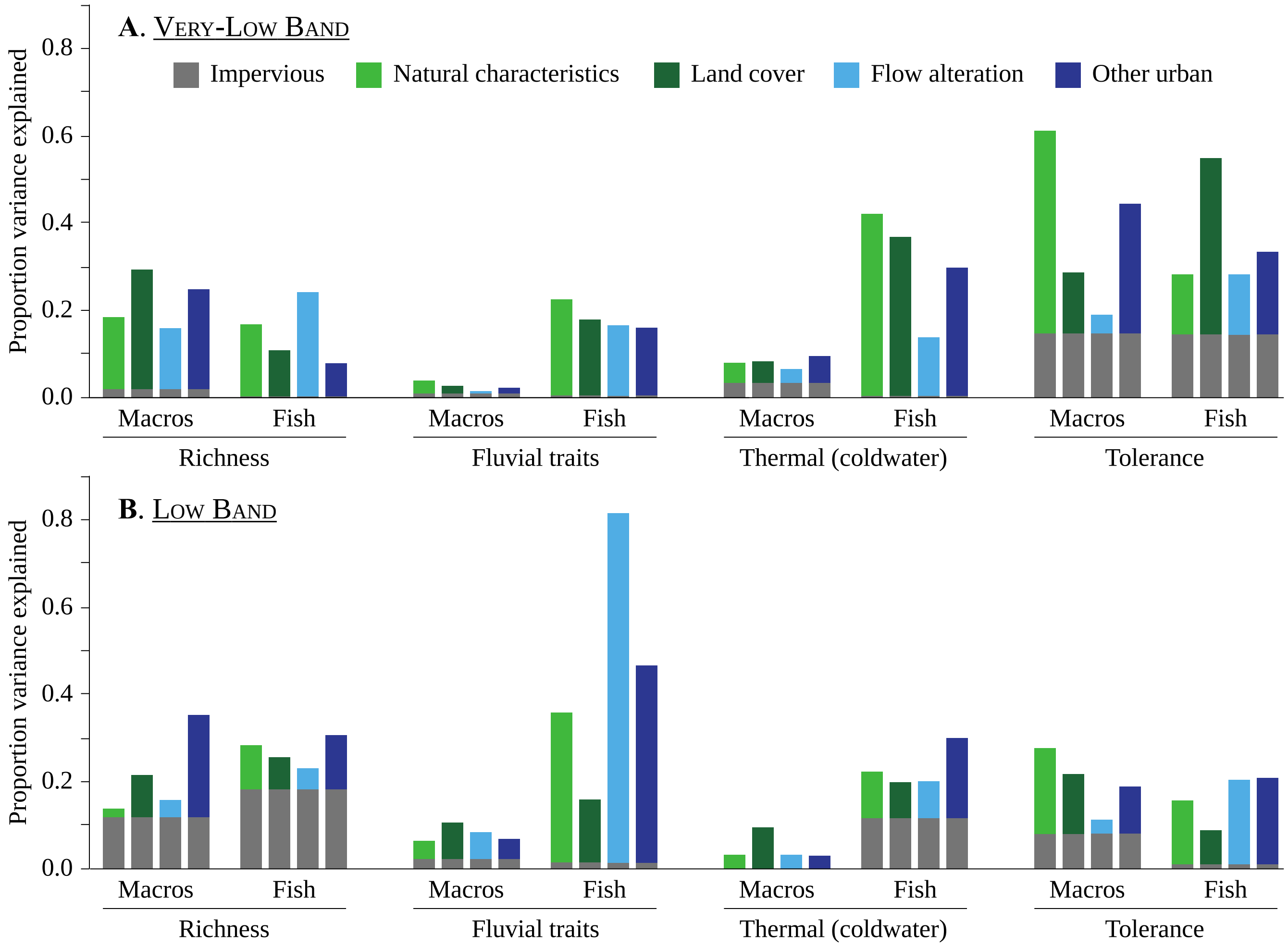


Figure 3.3. Additional variance explained by watershed-scale predictors within predictor categories of natural characteristics, land cover, flow alteration, and other urban measures, for (A) very-low (1–4%) and (B) low (7–10%) impervious bands.

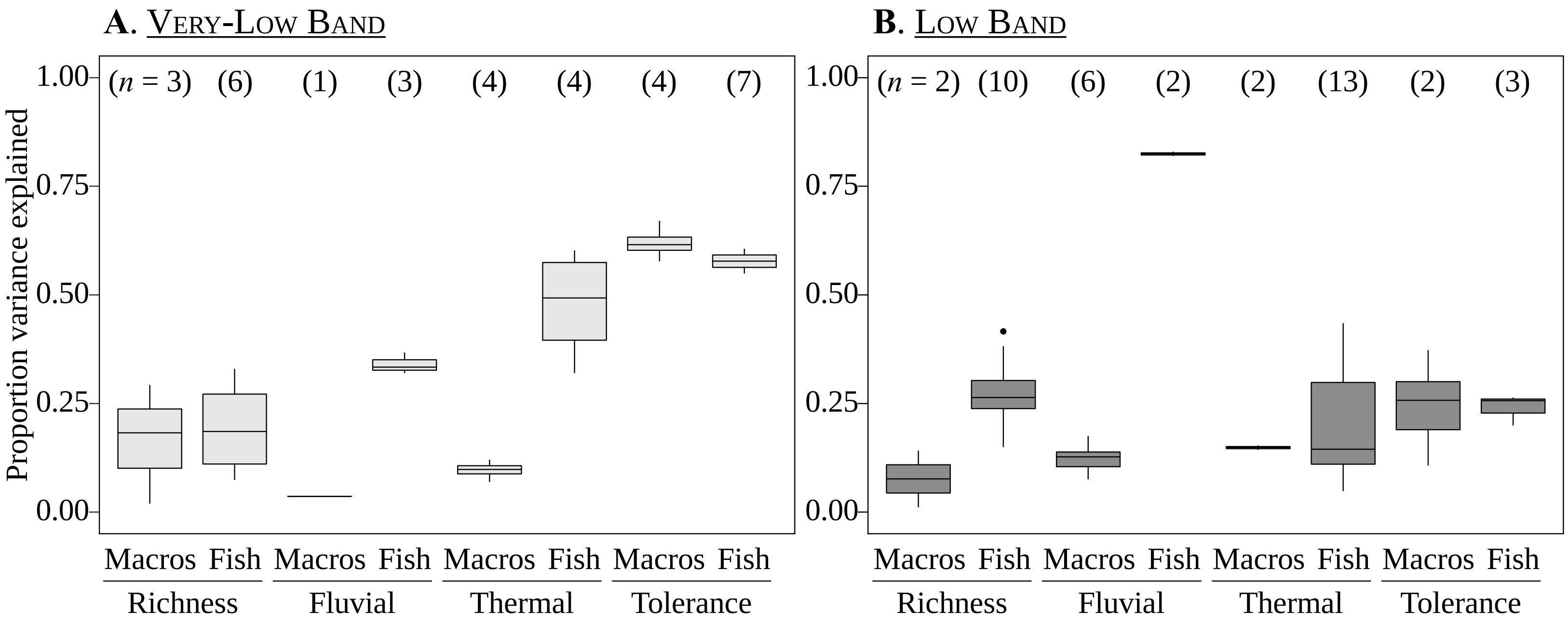


Figure 3.4 Box plots for variance explained by equally plausible models within the very-low band (A) and low band (B). Equally plausible models (< 2 AICc) are available in Appendix N.

CHAPTER 4

DISCUSSION AND CONCLUSIONS

4.1 Resistance and resilience: urbanization in context

Sites used in this study ranged from better to worse condition within a narrow range of impervious cover. While total impervious cover was an important variable for explaining many metrics of biotic condition, other variables at both reach and watershed scales explained additional variability, and in several instances were more important than impervious cover for explaining biotic condition. Predictors that were related to higher biotic integrity potentially indicate conditions that allow streams to resist the impacts of increasing watershed urbanization. At the reach-scale, higher biotic integrity was related such factors as habitat heterogeneity, more large wood, and colder water temperatures. Restoration should focus on strategies to reduce impacts that would degrade these in-stream conditions. Similarly, watersheds should be prioritized for protection with those characteristics potentially more resistant to urban disturbance, such as high-elevation regions that retain high biotic integrity despite higher dam density, more road crossings, and more flow alteration.

Since urbanization impacts are observed at all levels, including at the low end of the gradient, land use planning and zoning in undeveloped watersheds is essential for protecting stream ecosystems. Some of the options for land conservation include land acquisition, conservation easements, and regulations for natural resource protection (Cappiella et al. 2012). Undisturbed areas, such as heavily forested watersheds, particularly in high-elevation coldwater areas, can serve as refuge for aquatic biota during urban disturbances, as well as a source to repopulate an area post-disturbance. These areas should be prioritized for protection. Fitzgerald et al. (2012) found that in Vermont, high-gradient streams were more vulnerable to physical and biotic degradation due to the interaction of urbanization with natural watershed characteristics; this reinforces the notion of protecting high-elevation (often high-gradient headwaters). Protection strategies also manifest differently for macroinvertebrates and fishes. Since many macroinvertebrates have both aquatic and terrestrial life stages, protecting terrestrial habitat adjacent to streams is critical for dispersal and recolonization (Smith et al. 2009). Since fishes are constrained to the stream network, aquatic connectivity is vital to allow resilience of fish populations in response to urban disturbances such as increased flood frequency and thermal pollution.

4.2 Scale matters

This study parses potential predictor variables by whether they were collected at the reach scale or the watershed scale. The role of scale, such as at the reach, buffer, catchment, or regional level, has long been recognized to be important for investigating biotic responses to natural conditions or anthropogenic stressors (Allan 2004). In this study, selected watershed-scale predictors explained more variance than reach-scale predictors, but reach-scale predictors more frequently explained more variance in biotic assemblages (Table 4.1, Figure 4.1). Whether reach- or watershed-scale variables better explained biotic responses tended to be reinforced by lower AICc values for the models that explained more variance.

Many studies have compared biotic responses to urbanization at different scales, with sometimes conflicting results. For instance, Roy et al. (2003) found that reach-scale variables (e.g., sediment size, total suspended solids, specific conductance, turbidity) better explained macroinvertebrate indices than watershed-scale variables (e.g., land cover classification). When both macroinvertebrate and fish communities were used in the same region, however, Walters et al. (2009) found that overall, macroinvertebrates were better explained by land cover (i.e., watershed-scale) variables and fish better explained by geomorphology (i.e., reach-scale) variables. Furthermore, biotic responses were better explained when land cover, geomorphology, and water quality variables were combined, rather than when tested as three separate sets of predictors (Walters et al. 2009), indicating the interaction of environmental characteristics across scales.

Ecosystems are hierarchically structured, with patterns and processes operating on different scales (Frissell et al. 1986, Alberti 2005, Lowe et al. 2006, Parsons and Thoms 2007). While this study compares two scales, it does not combine predictors across scales to evaluate their combined power to explain biotic response. Relatively strong correlations ($|r \geq 0.50|$) were found between reach-scale and watershed-scale predictors in this study, including: higher elevation with more forest cover, higher slope, more riffle habitat, greater stream power, and coarse sediment; warmer air temperatures with less forest, less riffle and more run habitat, and smaller sediment; higher road density and higher mean and maximum specific conductance; and more dams with more open water and higher summer water temperatures. These indicate suites of factors that work in tandem, with potentially similar mechanisms influencing biotic assemblages in low-level urban streams.

It is important to match the scale of the disturbance with the scale relevant to biota (Townsend et al. 1997a, Parsons and Thoms 2007). Both macroinvertebrates and fishes were sampled in the field at a scale that matched the sections of stream where reach-scale variables were measured. Although both groups exhibit movement beyond the reach (macroinvertebrates via drift and emergence; fishes through greater mobility and migration), the scale at which both response and predictor variables were measured was better matched than those variables calculated at the watershed scale.

4.3 Metrics matter

The assessment of biotic condition in response to degradation requires careful consideration of metrics, in terms of which response metrics most accurately reflect the biotic assemblages of interest. Although fishes were better explained by additional variables at both the reach and watershed scale when impervious was constrained to low levels in this study, researchers that have assessed biotic responses along the gradient of urbanization have found that macroinvertebrates respond more predictably than fishes to a gradient of increasing urbanization (Walsh et al. 2005, Brown et al. 2009). Since taxonomic groups yielded differing information about which reach- and watershed-scale factors explained the most variance, we suggest both taxa be studied to allow for a more comprehensive understanding of urban impacts and how to mitigate them.

This study also provided support for measuring certain biotic metrics, such as macroinvertebrate tolerance, and suggested additional metrics that would improve understanding of predictor–response relationships. For instance, EPT richness or relative abundance is a more established metric that has been widely applied to detect sensitivity of macroinvertebrates to changing stream conditions, including urbanization. Since the macroinvertebrate flow and thermal trait metrics were not explained well by total impervious cover, nor the suite of reach or watershed factors tested, EPT would likely serve as a better metric of macroinvertebrate condition. Similarly, for fishes, fluvial fishes were explained well by the predictors tested, but low species richness and a high level overlap between coldwater and intolerant fishes did not render these useful metrics. Due to the limited species pool in the Northeast, including Massachusetts, specific species, such as brook trout, *Salvelinus fontinalis* that predominated in coldwater and intolerant fish relative abundance, would potentially serve as better indicators of biotic condition.

4.4 Compounding pressures from climate change

The hydrological and thermal impacts from urbanization on stream systems are compounded by climate change. Historical records show long-term increased stream water temperature warming—usually correlated with air temperature warming—and with the most rapid rates of increase in urbanized areas (Kaushal et al. 2010). Under climate change scenarios, air temperatures are projected to increase in the Northeast (Hayhoe et al. 2007), with more precipitation occurring during winter months as rainfall instead of snow (Guilbert et al. 2015). Minimum (i.e., colder) air temperature was an important variable in numerous biotic response models at the watershed scale, including fluvial, coldwater, and intolerant fishes, and macroinvertebrate flow traits and tolerance. As Herb et al. (2008) showed, the effects of thermal pollution are worse when air temperatures exceed stream temperatures (as in groundwater-fed streams), and as watershed impervious surface increases. Small streams with low flow are more susceptible to warming from stormwater since storm flows comprise the majority of discharge (Herb et al. 2008). Groundwater inputs provide important thermal refugia for coldwater species during summer months, and will be increasingly important refuge under increased warming scenarios (Snyder et al. 2015). Hilderbrand et al. (2014) found that streams with less thermal sensitivity, including those with groundwater inputs, would be more resilient to land use changes and climate change. Prioritizing protection of streams in cold, high-elevation areas, including those streams receiving high groundwater inputs, will be critical to maintaining biotic integrity under projected future conditions that compound the effects of urbanization and climate change.

4.5 Further research directions

The results of this study offer a starting point from which to further explore relationships between urbanization and aquatic biota. Several potential directions, including modifications to the study design and additional hypotheses, are discussed below. The study design could be modified is several ways to hone in on difference aspects of the impervious cover model (Schueler et al. 1994, 2009). This study used two bands of impervious cover in the effort to examine other variables that vary when the level of impervious is held constant. The bands in this study, however, spanned several percentage points, and were not separated by many percentage points. Even though the bands were relatively narrow, thresholds have been documented at numerous levels ranging 0.5–12% watershed impervious. Additional research could further constrain the level of impervious, with additional sites for greater explanatory power. For instance, the very-low band could be narrowed from 1–4% to 1–2% impervious, or the low band at 7–10% could concentrate on more sites at the 10% level. The difficulty in finding sites that met these criteria for this study could potentially be alleviated by (1) expanding biotic collections, such that sites not currently in the MDEP or MDFW databases are sampled, or (2) expanding the geographical scope beyond Massachusetts.

While this study focused on sites with a similar level of impervious cover, future studies could focus on sites with similar levels of biotic condition across the impervious gradient. Existing databases, such as the MDEP and MDFW datasets used in this study, are ripe for investigation into such questions. Two potential approaches would be to (1) select sites with better biotic condition despite higher imperious cover (e.g., >10% watershed impervious), or (2) select sites with worse biotic condition despite lower levels of impervious cover (e.g., <4% watershed impervious). By focusing on sites with similar biotic condition, this would allow better ability to test which factors act as buffers to resist higher levels of urbanization, or conversely, which factors act as constraints that limit higher attainment of biotic condition or make a stream more vulnerable to the effects of urbanization.

This study found tentative support for some factors that might confer resistance to biota in streams subjected urbanization, such as higher habitat heterogeneity, more dissolved oxygen, more large wood, and colder temperature (both air and water temperatures). These factors could be further investigated to see if the same variables apply to other regions or a broader suite of suites. Other researchers have also postulated factors that might confer resistance in urbanizing streams that were not tested in this study. Such additional factors include: high water table depth, less groundwater contribution to base flow, and low groundwater recharge areas (Bhaskar et al. 2016); already hydrologically flashy systems (Hale et al. 2016); snow-dominated systems (Hale et al. 2016); permeable soils (Hopkins et al. 2015, Bhaskar et al. 2016), including those soils that are shallow and dense (Poff et al. 2006a); naturally high pH and conductivity (Utz et al. 2016); and naturally warmer stream temperatures that would induce less thermal stress (Hale et al. 2016).

The modeling used in this study employed generalized linear models and generalized linear mixed models, with additive effects. Non-linear and interactive effects have been shown to explain biotic condition across the gradient of urbanization (King et al. 2011, Fitzgerald et al. 2012), and might also be useful when describing condition at low levels of impervious cover. Furthermore, cumulative effects, such as those integrated across the watershed, have potential for further exploration.

4.6 Conclusion

Urbanization is increasing nationwide, including in the Northeast region. The dramatic rise in exurban, low-density development in formerly rural areas (Brown et al. 2005, Hansen et al. 2005) means that many streams are—or will be—subject to the impacts from low levels of urbanization and impervious cover (Theobald et al. 2009). Understanding what factors drive the variability in low-level urban streams can help determine which characteristics make streams more susceptible to urban effects. This can also lead to an understanding of which factors confer resistance to urbanization, thereby helping prioritize such area for protection. Prioritizing areas that facilitate resistance and resilience will allow biota to recover from anthropogenic disturbances in an increasingly urbanized world.

Table 4.1 Comparison of whether reach- or watershed (WS)-scale predictors explained more variance for each biotic response metric, based on the mean R^2 for equally plausible models (Appendix I, Appendix N). Reach- and watershed- scale predictors were compared for both bands analyzed together (n = 20) as well as bands analyzed separately (very low = 1–4%, low = 7–10%). Shading in gray denotes when single-band results differed from both-band results.

Response group	Both bands		Very-low band		Low band	
Response variable	Reach > WS	WS > Reach	Reach > WS	WS > Reach	Reach > WS	WS > Reach
Richness						
Macroinvertebrate taxa richness	X		X		X	
Fish species richness	X		X		X	
Flow traits						
Macroinvertebrate flow traits, rel abund (%)	X		X		X	
Fish, fluvial rel abund (%)		X		X		X
Thermal traits						
Macroinvertebrates, coldwater rel abund (%)		X	X			X
Fish, coldwater rel abund (%)		X		X	X	
Tolerance						
Macroinvertebrate tolerance index	X			X	X	
Fish, intolerant rel abund (%)	X			X	X	

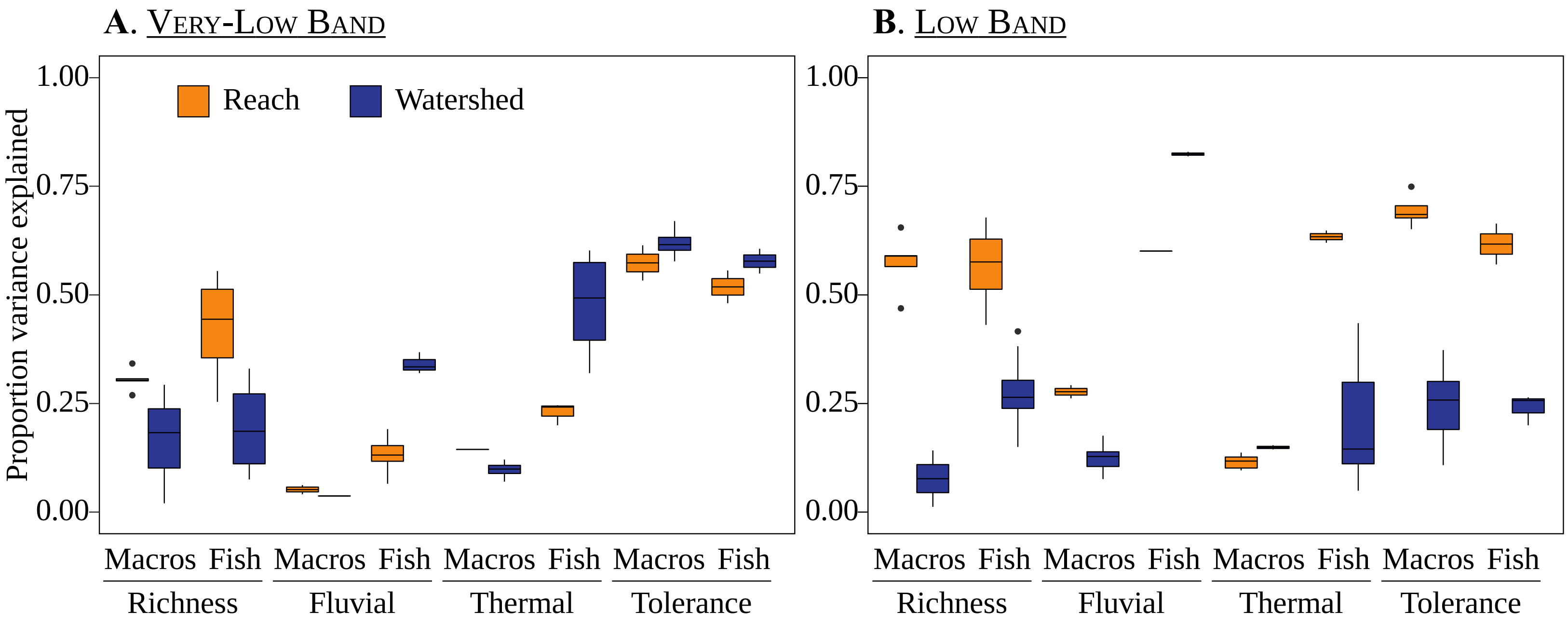


Figure 4.1. Variance explained by equally plausible models for both reach- and watershed-scale factors, for both bands analyzed together. Each box represents the range of R^2, pseudo-R^2, or conditional-R^2 for sets of equally plausible models (< 2 ΔAICc; Appendix I, Appendix N) for each biotic response metric of richness, fluvial traits, thermal traits, and tolerance. Models with reach-scale variables tended to explained more variance in biotic assemblage metrics than models with watershed-scale variables, except in the case of fluvial fishes and coldwater macroinvertebrates. Bands refer to very low = 1–4% and low = 7–10% impervious cover.

APPENDICES

APPENDIX A:

SAMPLING SITES AND CODES

Appendix A. Sampling identifiers for the 40 stream sites used in this study. Sites were sourced from existing biotic databases from Massachusetts Department of Environmental Protection (MDEP) and Massachusetts Division of Fisheries and Wildlife (MDFW). Additional sites were sampled during 2015–2016 such that each site had both macroinvertebrates and fishes. Codes in bold represent the UniqueIDs that are used in subsequent tables to identify each site; sites are alphabetically by bolded code.

		Coordinates		MDEP codes					MDFW codes			Sampling date	
Stream name	Town name	Latitude	Longitude	Unique ID (B)	Unique ID (W)	SiteID	BenSampID	ProjectCode	SampleID	SARIS	New sites (K)	Macros	Fish
Sevenmile	North Attleborough	41.9516	-71.3419	**B0052**		SM00	2007051	Ten Mile 2007	SID5460	5233675		9/20/07	6/17/15
Stop	Medfield	42.1590	-71.3030	**B0067**		SR03	2007020.A	Charles 2007		7239925		7/20/07	10/7/15
Beaver	Sharon	42.1345	-71.1762	**B0139**		BB01	2009019	Boston Harbor/Neponset 2009	SID2527	7341400		7/13/09	8/25/08
Massapoag	Sharon	42.1205	-71.1643	**B0143**		9BOB	2009047	Boston Harbor/Neponset 2009	SID4786	7341375		9/18/09	8/7/13
Fish	Boxford	42.6601	-71.0076	**B0157**		FB00	2005077	Ipswich 2005	SID5464	9253850		8/12/05	7/14/15
Miles	Ipswich	42.6610	-70.8450	**B0439**		MR01	2005051.1	Ipswich 2005		9253650		7/25/05	10/6/15
Gravelly	Ipswich	42.6610	-70.9040	**B0440**		GB01	2005052	Ipswich 2005		9253725		7/25/05	10/6/15
Beaver	Templeton	42.5951	-72.1216	**B0450**		BB01	2005088.1	Millers 2005	SID4952	3523600		9/13/05	8/12/13
Pond	Westfield	42.1248	-72.7220	**B0575**		PNDB00.1	2006094	Westfield 2006	SID5465	3208600		9/5/06	8/12/15
North	Medfield	42.1972	-71.3284	**B0612**		W1586	2007015	Charles 2007	SID5463	7239875		7/18/07	7/16/15
Jabish	Belchertown	42.2822	-72.3919	**B0650**		JB00	2008052	Chicopee 2008	SID1956	3626550		9/10/08	7/29/06
South Branch Mill	East Longmeadow	42.0863	-72.4803						SID5466		**K0001**	9/14/14	8/12/15
Stony	South Hadley	42.2535	-72.5917								**K0002**	9/21/14	10/8/15
Sucker	Pepperell	42.6968	-71.6102	B0318					**SID2171**			8/10/15	10/2/15
Mill	Concord	42.4575	-71.3329						**SID2507**			7/9/15	2008
Mill	Blackstone	42.0489	-71.5203						**SID2630**	5131200		9/19/14	8/19/08
French	Oxford	42.1892	-71.8984						**SID3026**			7/22/15	9/23/09
Little	Charlton	42.1386	-71.9118						**SID3029**			7/24/15	9/17/09
unnamed	Westminster	42.5563	-71.8749						**SID3054**	8145040		9/6/14	8/6/09
James	Ayer	42.5794	-71.5884						**SID4016**	8143925		8/26/14	7/17/12
Cronin	Grafton	42.1849	-71.7120						**SID4928**	5132625		8/25/14	6/27/13
Bread and Cheese	Westport	41.6327	-71.0604	B0827	**W0344**	RSN-BCB01	2014014.A	RSN 2014		9560150		7/14/14	9/5/13
Chicken	Medway	42.1506	-71.4289	B0690	**W2152**	MA09A-164	2010030	MA09A 2010	SID4546	7240175		8/2/10	8/10/11
Sewall	Sherborn	42.2222	-71.3544		**W2154**	MA09A-106			SID5462	7239750		7/30/15	7/16/15
South Branch Souhegan	Ashby	42.7098	-71.8517	B0671	**W2158**	MA09A-101	2010017	MA09A 2010	SID4553	8451850		7/19/10	8/13/10
Coys	North Brookfield	42.2622	-72.1066	B0897	**W2166**	MAP2-523	2014025	MAP2 2014				7/22/14	8/26/14
Monoosnoc	Leominster	42.5266	-71.7569	B0703	**W2180**	MAP2-007	2011014	MAP2 2011	SID4581			7/6/11	2011
Catacoonamug	Shirley	42.5531	-71.6695	B0708	**W2186**	MAP2-023	2011019	MAP2 2011	SID4582	8144525		7/11/11	8/12/11
Whitman	Westminster	42.5821	-71.9026	B0716	**W2194**	MAP2-035	2011011	MAP2 2011	SID4614	8145075		7/5/11	8/9/11
Ellinwood	Athol	42.5562	-72.2310	B0720	**W2199**	MAP2-045	2011016	MAP2 2011	SID4595	3522850		7/7/11	8/26/11
Bowers	Harvard	42.5319	-71.5791	B0725	**W2205**	MAP2-055	2011018	MAP2 2011	SID4583	8144400		7/11/11	8/12/11
unnamed	Charlton	42.1401	-71.9985		**W2217**	MAP2-079			SID5461	4100000		7/30/15	7/14/15
Broad	Easthampton	42.2502	-72.6589	B0879	**W2219**	MAP2-526	2014024	MAP2 2014				7/21/14	9/18/14
Trout	Holden	42.3838	-71.8378	B0743	**W2226**	RSN-TR01	2014007	RSN 2014	SID4584	8145350		7/7/14	8/18/11
Kinderhook	Hancock	42.5450	-73.3128	B0793	**W2256**	MAP2-182	2012043	MAP2 2012		1202150		7/25/12	8/22/12
East Branch Housatonic	Dalton	42.4739	-73.1412	B0795	**W2258**	MAP2-186	2012032	MAP2 2012		2105275		7/18/12	9/25/12
Doggett	Rochester	41.7279	-70.7981	B0832	**W2374**	MAP2-328	2013003	MAP2 2013		9559050		7/2/13	8/22/13
Fall	Freetown	41.7557	-70.9831	B0840	**W2382**	MAP2-360	2013010	MAP2 2013		6236475		7/9/13	8/30/13
Pine Tree	Milton	42.2434	-71.0944	B0844	**W2385**	MAP2-366	2013038	MAP2 2013		7341075		7/25/13	9/10/13
Pond	Montague	42.5529	-72.5195	B0887	**W2453**	MAP2-534	2014041	MAP2 2014				7/30/14	6/18/14

APPENDIX B:

RAW BIOTIC DATA MATRICES

Appendix B.1. Macroinvertebrate taxa abundances collected at each sampling site. Sites are arranged alphabetically by code from left to right. FinalID refers to the lowest level to which a taxon was identified. FinalIDs are arranged alphabetically from top to bottom. Taxa classifications for phylum, class, order, family, subfamily, tribe, genus, and final ID are found in Appendix C.1. All taxa are listed for 20 sites, then the taxa list repeats for the remaining 20 sites.

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Ablabesmyia sp.												1	8							
Acentrella parvula												3								
Acentrella turbida																				
Acerpenna macdunnoughi														3						
Acerpenna sp.																				
Acroneuria abnormis									2								3	1	3	
Acroneuria sp.					7						1									
Aeschnidae																				
Amnicola sp.																				
Anchytarsus bicolor																				
Ancylidae																				
Ancyronyx variegata													4							
Antocha sp.				1				1				1		4		4			1	
Apatania sp.																3				
Atherix sp.																				
Aulodrilus pigueti																				
Aulodrilus pluriseta																				
Aulodrilus sp.		1																		
Baetidae																	2			
Baetis flavistriga				9					2					2		1				
Baetis flavistriga/intercalaris																				
Baetis intercalaris									2				2							
Baetis pluto																13				
Baetis sp.									6	1						18	7	1	10	
Baetis tricaudatus									1										1	
Bezzia/Palpomyia sp.			1																	
Boyeria sp.																				
Boyeria vinosa									1				2	2						2
Brachycentrus americanus																				
Brachycentrus appalachia																				
Brachycentrus numerosus												5		2						
Brillia sp.												1	3			1				
Brundiniella sp.																				
Caecidotea communis																				
Caecidotea sp.						1	1					1	3		66			1		
Caenis sp.																				
Calopterygidae											1			3	1					
Calopteryx sp.												1	1							
Cambaridae												1								
Cardiocladius obscurus																				

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Centroptilum sp.																				
Ceraclea sp.														1			2			
Ceratopogon sp.															1					
Ceratopogonidae	1																			
Ceratopogoninae												1	2							
Chaetocladius sp.																				
Chauliodes rastricornis																				
Chelifera sp.																				
Cheumatopsyche sp.	5	37	4	7			1	5	8	6	7	5	8	15	5	10	74	13	32	49
Chimarra aterrima	14		6	20	2			2	24	15		1		9		37	4	11	12	98
Chimarra obscura		1		13												29	22	3		
Chimarra sp.																				
Chironominae													2							
Chironomini												6	3			1		1		
Chironomus sp.						15							1							
Cladotanytarsus sp.												2								
Clinocera sp.									1											
Coenagrionidae	1													3	1					
Conchapelopia sp.					7		1	7												
Coptotomus sp.																				
Corbicula fluminea												1								
Cordulegaster sp.										1				1						
Corduliidae																				
Corixidae																				
Corydalus cornutus																	1			
Corynoneura sp.							1	2		1	2	1	9	4			1			
Crangonyx sp.												2								17
Cricotopus bicinctus		1		1					1			2	6	10					12	
Cricotopus sp.												1	1	1					1	
Cricotopus sylvestris																				
Cricotopus trifascia									1											
Cricotopus/Orthocladius sp.												2	2	3					4	
Cryptochironomus sp.		1											1		3					
Cryptotendipes sp.													4							
Culicidae																				
Dannella simplex																				
Demicryptochironomus sp.																				
Dero nivea/obtusa						2														
Diamesa sp.	1								6											
Dicranota sp.					4						7			2						2

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Dicrotendipes sp.						1						1	1							
Dineutus sp.																				
Diphetor hageni																				
Diplectrona modesta			4						1											
Diplectrona sp.																				
Diplocladius cultriger																			16	7
Diplocladius sp.														2				8		
Dixella sp.																				
Dolophilodes distinctus																				
Dolophilodes sp.											7									
Drunella cornutella																				
Dubiraphia sp.												13	10							
Dytiscidae																				
Ectopria nervosa	2										1									
Elmidae	7										2			11		3	2	1		4
Empididae			1								1									
Enchytraeidae																				
Epeorus sp.																	1			
Ephemerella sp.											1						1		30	
Ephemerella subvaria											3									
Erpobdella punctata																	1			
Erpobdella sp.																				
Eukiefferiella brehmi gr.																			1	
Eukiefferiella devonica gr.																1				
Eukiefferiella pseudomontana gr.																				
Eukiefferiella sp.			3															5		
Eurylophella funeralis																				
Eurylophella sp.	2							1						6						
Ferrissia sp.												6					5			
Gammarus sp.		16	6		2	8	51								20					
Glossosoma sp.			1	1						2				3		1	5	1	9	
Goera sp.																				
Gomphidae								1						1						
Gyraulus parvus							1													
Gyrinus sp.																				
Helobdella sp.																				
Helobdella stagnalis															2					
Helophorus sp.																				
Hemerodromia sp.	1			2	1				1			15		4						
Heptageniidae												1								

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Hexatoma sp.												1				2				
Hyalella sp.															183					
Hydrobaenus sp.																				
Hydrobiidae						1									3		2			
Hydropsyche betteni	3	16		12	9		17	4	10	7		1		68		26	9	68	52	49
Hydropsyche morosa																				
Hydropsyche morosa gr.									2										22	
Hydropsyche sp.					21			2	4							1				
Hydropsyche sparna			3								1					33	13	16	8	
Hydropsyche ventura																				
Hydropsychidae														11			1	8		
Hydroptila sp.									2					2						
Hygrobates sp.		1										5			1					
Isonychia bicolor																5	7	7		
Isonychia sp.																				
Isoperla sp.																				
Kiefferulus sp.						2														
Labiobaetis frondale												5	1	5						
Labrundinia sp.													3							
Lebertia sp.	1											3		1						
Lepidostoma sp.											1									
Leptoceridae												3								
Leptophlebiidae								2								1				
Leuctra sp.			9		4						2									
Leuctridae/Capniidae														4			1			
Limnephilidae																				
Limnophyes sp.											1									
Lumbricina																			1	
Lumbriculidae		1		2	1		3			1	6			3						
Lymnaeidae																				
Lype diversa												4	2	3						
Maccaffertium modestum		6									3							2		
Maccaffertium sp.			1	7				12		3	6		8				6	2		
Macronychus glabratus												1	6	3			5			
Macrostemum sp.																	7			
Macrostemum zebratum																3				
Menetus dilatatus																	2			
Micrasema sp.	2							5	1							7	2		3	
Microcylloepus pusillus			11	5									1				15		6	
Micropsectra sp.			2		1			13			9									7

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Micropsectra/Tanytarsus sp.	1																			
Microtendipes pedellus gr.						1					1	3		10		3				
Microtendipes rydalensis gr.			1		9								8					2		
Microtendipes sp.																				
Microvelia sp.																				
Molanna sp.																				
Mystacides sepulchralis											1	9								
Naidinae																				
Nais behningi						1														
Nais communis/variabilis	1					8														
Nais elinguis						2														
Nais sp.																				
Nanocladius sp.													1							
Natarsia sp.												3								
Nemata												5								
Neophylax oligius																				
Neoplasta sp.																		1		
Neoporus sp.																				
Nigronia serricornis					2		3	2		1	3			2			4	6		3
Nigronia sp.																				
Nilotanypus sp.																	1	1		
Nilothauma sp.																				
Notonecta sp.																				
Nyctiophylax sp.																				
Odontomesa sp.																				
Oecetis persimilis																				
Oecetis sp.												1	4				1			
Ophiogomphus sp.														1						
Optioservus ovalis											1			3			1			
Optioservus sp.			2		3									13		16	2			8
Optioservus trivittatus																1				
Oribatida																				
Orthocladiinae												5	10					1		
Orthocladiinae Sp C																				
Orthocladius (Symposiocladius) lignicola																				
Orthocladius carlatus									1											
Orthocladius dubitatus																				
Orthocladius sp.									1											
Ostracoda												1								
Oulimnius latiusculus	13		6		1			1	5	11	3			11		18	1		3	9

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Oxyethira sp.																				
Pagastia sp.																				
Parachaetocladius sp.											1									
Paracladopelma sp.													1							
Paracricotopus sp.	2																			
Paragnetina media									7								5	14		
Paragnetina sp.																				
Parakiefferiella sp.												10	4				15	1		
Paralauterborniella sp.													2							
Paraleptophlebia sp.	1										1									
Paramerina sp.												1								
Parametriocnemus sp.	5				4	1		2	1	4		5	1			3		4	1	14
Paraphaenocladius sp.																				
Paratanytarsus sp.						10						2	1							
Paratendipes sp.												7								1
Perlesta placida																				
Perlidae																		2		
Perlodidae																				
Phaenopsectra sp.												8	2		1					
Philopotamidae				2																
Phylocentropus sp.																				
Physa sp.																				
Physidae	1																			2
Pisidiidae	6	2		1			2	20		1		12	6	4	13		23	20		5
Pisidium sp.																	2			
Planorbella sp.																				
Planorbidae																				
Platycentropus sp.																				
Plauditus sp.		8									2			1						
Polycentropus sp.													6							
Polypedilum aviceps			4		2				1	4	9								6	5
Polypedilum fallax gr.												1								
Polypedilum flavum				5		3		1					6			7		1		3
Polypedilum halterale gr.												8	8							
Polypedilum illinoense gr.					1					1			2							3
Polypedilum laetum																				
Polypedilum scalaenum																				
Polypedilum scalaenum gr.															1					
Polypedilum sp.	1											1	19				1			
Polypedilum tritum						2						1			1					

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Potthastia longimana gr.																		4		
Pristina aequiseta						1														
Pristinella osborni	1																			
Probezzia sp.												3								
Procladius sp.															1					
Prodiamesa sp.																				
Promoresia sp.					1															
Promoresia tardella			14					3	1	4	5			4		16	1	3	49	
Psephenus herricki					1						2					13			1	
Pseudolimnophila sp.																			1	
Psilotreta frontalis																				
Psychomyia flavida																				
Psychomyiidae																				
Pteronarcys biloba									1											
Pycnopsyche guttifera														1						
Pycnopsyche lepida gr.														1						
Pycnopsyche sp.																				
Ranatra sp.																				
Rheocricotopus robacki						2		1												
Rheocricotopus sp.	4											8	8			1	2			
Rheotanytarsus exiguus gr.				3		15	12	1	2			7	58		2		31	62	8	1
Rheotanytarsus pellucidus		2			2			1				8	22		1		1	5	1	3
Rheotanytarsus sp.													2				3	18	1	
Rhyacophila carolina																				
Rhyacophila fuscula																1	1			
Rhyacophila minor											1			1						
Rhyacophila sp.			1													2				
Ripistes parasita																				
Serratella serrata																				
Serratella serratoides																				
Serratella sp.									1											
Sialis sp.																				
Simulium sp.		4	6	10	2	5		1	7	11	2	4		33		7	6	2	5	6
Simulium verecundum cplx.			5	4													1	1		
Slavina appendiculata																				
Sperchon sp.																2		2	1	
Sperchonopsis sp.										1				1						
Sphaerium sp.				1											2					
Sphaeromias sp.															1					
Staphylinidae																				

Appendix B.1 continued

FinalId	B0052	B0067	B0139	B0143	B0157	B0439	B0440	B0450	B0575	B0612	B0650	K0001	K0002	SID2171	SID2507	SID2630	SID3026	SID3029	SID3054	SID4016
Stempellina sp.					1															
Stempellinella sp.												35	1							1
Stenacron interpunctatum																1				
Stenelmis crenata	23									8	2					1			1	2
Stenelmis sp.		8	6		1	2		5					1	4	1	19		7		10
Stenochironomus sp.													1				1			
Stictochironomus sp.												1								
Stylaria lacustris																				
Sublettea coffmani																				
Synorthocladius sp.																				
Tabanidae												1								
Tallaperla maria																				
Tanypodinae												2	1							
Tanytarsini												1		1				1		
Tanytarsus sp.					2	10		6		3		8	16		3			1		11
Teloganopsis deficiens																			13	
Thienemanniella sp.											1	3	5	5		1			1	
Thienemannimyia gr.	1	1								2		5	8	1	1	1		1		4
Tipula sp.													1	1			1			
Tipulidae	7															1				
Torrenticola sp.																		1	4	
Tribelos sp.													7							
Trichoptera																				
Trissopelopia sp.																				
Trombidiformes														1			1			
Tropisternus sp.																				
Tubificinae IWB						2														
Tubificinae IWH																				
Tubificinae w capilliform setae												2	2		1					1
Tubificinae wo capilliform setae												24	10		11					
Tvetenia paucunca	3		5	1	3		7	3	2	14	3	1		9		10		5	10	7
Tvetenia sp.																				1
Tvetenia vitracies		1														1	2		3	
Vejdovskyella comata																				
Xenochironomus xenolabis																	2			
Xylotopus par													1							
Zavrelimyia sp.																				
Zygoptera					8															

Appendix B.1. Macroinvertebrate taxa abundances collected at each sampling site. Sites are arranged alphabetically by code from left to right. FinalID refers to the lowest level to which a taxon was identified. FinalIDs are arranged alphabetically from top to bottom. Taxa classifications for phylum, class, order, family, subfamily, tribe, genus, and final ID are found in Appendix C.1. All taxa are listed for 20 sites, then the taxa list repeats for the remaining 20 sites. The following eight tables are the second half of the sites.

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Ablabesmyia sp.						9											1		1	
Acentrella parvula																				
Acentrella turbida												2			3	2				
Acerpenna macdunnoughi														1						
Acerpenna sp.	3		1																	1
Acroneuria abnormis					6					2				1						
Acroneuria sp.		3												9						
Aeschnidae						3												1		
Amnicola sp.	1																1			
Anchytarsus bicolor											1									
Ancylidae																		41		
Ancyronyx variegata																			6	
Antocha sp.							1					8				6				
Apatania sp.																				
Atherix sp.															1					
Aulodrilus pigueti																		10		
Aulodrilus pluriseta																	3			
Aulodrilus sp.																				
Baetidae											1				4					
Baetis flavistriga							5		1			2		3		1				
Baetis flavistriga/intercalaris												7								
Baetis intercalaris							4					1				5				
Baetis pluto							1													
Baetis sp.					1		2					1	36	1						
Baetis tricaudatus										2					14					
Bezzia/Palpomyia sp.				2																
Boyeria sp.												1								
Boyeria vinosa					1							1								
Brachycentrus americanus															17					
Brachycentrus appalachia														8						
Brachycentrus numerosus					1					1			10							
Brillia sp.													2							
Brundiniella sp.													2							
Caecidotea communis																			2	
Caecidotea sp.	2	1		52													2	34	28	
Caenis sp.						2												5		
Calopterygidae	6																	2		11
Calopteryx sp.													1							4
Cambaridae																				
Cardiocladius obscurus							1									1				

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Centroptilum sp.						45														
Ceraclea sp.																				
Ceratopogon sp.																				
Ceratopogonidae																			1	
Ceratopogoninae						3							2				1			
Chaetocladius sp.								1												
Chauliodes rastricornis																		2		
Chelifera sp.						1							3							
Cheumatopsyche sp.	6	2	12	22			5	16	3	12	22	21	2	7			6	10	10	4
Chimarra aterrima	5	3	9		2		22		2		11	7		2						25
Chimarra obscura							6													
Chimarra sp.							1													
Chironominae																				
Chironomini	1			2		2							2						2	
Chironomus sp.			1																	
Cladotanytarsus sp.	1																			
Clinocera sp.																				
Coenagrionidae						4												68		
Conchapelopia sp.																				
Coptotomus sp.																		1		
Corbicula fluminea																				
Cordulegaster sp.	3			2	1															
Corduliidae																		1		
Corixidae						5											1	1		
Corydalus cornutus																				
Corynoneura sp.	2	1		2		1			1	1			2	1					2	1
Crangonyx sp.																		1		
Cricotopus bicinctus						3						14				1				
Cricotopus sp.						4						6								
Cricotopus sylvestris																		6		
Cricotopus trifascia																				
Cricotopus/Orthocladius sp.				1		1						5	1	2	7	11				
Cryptochironomus sp.				1									2							
Cryptotendipes sp.						2														
Culicidae						6														
Dannella simplex						3							1							
Demicryptochironomus sp.						1														
Dero nivea/obtusa																				
Diamesa sp.							5													
Dicranota sp.	7	2	1		7					1	1		1	6	1					2

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Dicrotendipes sp.																				
Dineutus sp.						1														
Diphetor hageni															2					
Diplectrona modesta										1										
Diplectrona sp.													1	3						
Diplocladius cultriger																				
Diplocladius sp.												5							4	1
Dixella sp.						2														
Dolophilodes distinctus														18						16
Dolophilodes sp.					3															
Drunella cornutella															1					
Dubiraphia sp.						4														
Dytiscidae													1							
Ectopria nervosa												1								
Elmidae	5	11																		
Empididae		1		1										1						
Enchytraeidae	1																			
Epeorus sp.																				
Ephemerella sp.															2	7				
Ephemerella subvaria																				
Erpobdella punctata																				
Erpobdella sp.		1																		
Eukiefferiella brehmi gr.														4						
Eukiefferiella devonica gr.																1				
Eukiefferiella pseudomontana gr.																3				
Eukiefferiella sp.		4																		
Eurylophella funeralis						1														1
Eurylophella sp.												3								
Ferrissia sp.																	11	2		
Gammarus sp.		3		114													73		12	
Glossosoma sp.		2					1					7		4						
Goera sp.																1				
Gomphidae	1	1																		
Gyraulus parvus																				
Gyrinus sp.													1							
Helobdella sp.		8		1																
Helobdella stagnalis																				
Helophorus sp.												1								
Hemerodromia sp.		1	1								1	2				1				2
Heptageniidae					1								2	1						

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Hexatoma sp.					1															
Hyalella sp.						11											26	34		
Hydrobaenus sp.																			1	
Hydrobiidae	1																10			
Hydropsyche betteni	1	1	14	26	1		30	59			28	10		1						77
Hydropsyche morosa																3				
Hydropsyche morosa gr.		1			8				7											
Hydropsyche sp.			23		3			10		2				8						16
Hydropsyche sparna		12			4		3		25	6		3		3	2	1				
Hydropsyche ventura										1				1						
Hydropsychidae			6		8							7	2							
Hydroptila sp.						1														
Hygrobates sp.			1																	
Isonychia bicolor																				
Isonychia sp.					1							1				6				
Isoperla sp.										1										
Kiefferulus sp.																				
Labiobaetis frondale				3		59														
Labrundinia sp.						1											2			
Lebertia sp.																			1	
Lepidostoma sp.										1			2	2						
Leptoceridae																	2			
Leptophlebiidae	2					8							3			2				
Leuctra sp.		14			11	1			1	8			7	27	8					3
Leuctridae/Capniidae												1								
Limnephilidae	4												4							
Limnophyes sp.	1	1											4							
Lumbricina																				
Lumbriculidae	7	10		3				1		1	1		1	2			1			2
Lymnaeidae	1					2											8	1		
Lype diversa													3						9	
Maccaffertium modestum							1	12					4				2			1
Maccaffertium sp.	1		1			2			1		7	1	1	1			3			19
Macronychus glabratus	3			1								7								
Macrostemum sp.																				
Macrostemum zebratum																				
Menetus dilatatus				2													49			
Micrasema sp.										2				9						
Microcylloepus pusillus		1																		
Micropsectra sp.	7	15			3	5			9	4			22	44	3	2		2	18	7

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Micropsectra/Tanytarsus sp.		63																		
Microtendipes pedellus gr.	1	1	2	3		3			1			23	2	1		3				
Microtendipes rydalensis gr.						1			1	1		1	6	14		3				
Microtendipes sp.						1														
Microvelia sp.						3														5
Molanna sp.				1																
Mystacides sepulchralis	1																			
Naidinae																		4		
Nais behningi																				
Nais communis/variabilis							1	1												
Nais elinguis																				
Nais sp.		5												2						1
Nanocladius sp.																1	1			
Natarsia sp.																				
Nemata																				
Neophylax oligius		1																		
Neoplasta sp.														2	1					
Neoporus sp.																		1		
Nigronia serricornis		3			2			1	3	1	2	1		4		2				16
Nigronia sp.													1							
Nilotanypus sp.	1		1									1								
Nilothauma sp.									2											1
Notonecta sp.						1														
Nyctiophylax sp.	1																			
Odontomesa sp.													1							
Oecetis persimilis																	1			
Oecetis sp.				1													1		1	
Ophiogomphus sp.																				
Optioservus ovalis	2	34																		2
Optioservus sp.			1									3								
Optioservus trivittatus																				
Oribatida	1																			
Orthocladiinae		6										2		2		1			4	
Orthocladiinae Sp C				1																
Orthocladius (Symposiocladius) lignicola													1				1			
Orthocladius carlatus																				
Orthocladius dubitatus															3	2				
Orthocladius sp.																				
Ostracoda																				
Oulimnius latiusculus	8	32	1		2				1	3					1	1				13

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Oxyethira sp.				1														7		
Pagastia sp.													5			1				
Parachaetocladius sp.	1	3			1					2										
Paracladopelma sp.																				
Paracricotopus sp.																				
Paragnetina media																				
Paragnetina sp.																3				
Parakiefferiella sp.												8	8							
Paralauterborniella sp.						4							8							
Paraleptophlebia sp.															2				5	
Paramerina sp.						4														
Parametriocnemus sp.	35	1		2	3	2					1		3	2		2				8
Paraphaenocladius sp.																	1			
Paratanytarsus sp.	1					10						1	1					31	4	
Paratendipes sp.				1		10							5				1		28	
Perlesta placida		2							1											
Perlidae					1															
Perlodidae											1									
Phaenopsectra sp.	1					2								1					10	
Philopotamidae	3																			4
Phylocentropus sp.				3									1							
Physa sp.				2																
Physidae						3							2				1		1	
Pisidiidae	16	3		33	2			1				1		4			52			
Pisidium sp.				8													9			
Planorbella sp.				1																
Planorbidae						2														
Platycentropus sp.				1																
Plauditus sp.																4				
Polycentropus sp.						1								2						
Polypedilum aviceps	13			3			3		1	1		1	18	14	1	9				76
Polypedilum fallax gr.	1											1	6							
Polypedilum flavum			6				4													
Polypedilum halterale gr.	5																		1	
Polypedilum illinoense gr.	12	1	1			31	1						16				3	14	26	8
Polypedilum laetum	1																			
Polypedilum scalaenum																	1			
Polypedilum scalaenum gr.				1									2							
Polypedilum sp.		4										1		1	1					
Polypedilum tritum			1										2		1	1		5		

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Potthastia longimana gr.																	1	1		
Pristina aequiseta																				
Pristinella osborni																				
Probezzia sp.	2																			
Procladius sp.				1		3												1		
Prodiamesa sp.													1							
Promoresia sp.																				
Promoresia tardella		7			15				5	12			2	37						
Psephenus herricki		3									1	6				1				
Pseudolimnophila sp.																				
Psilotreta frontalis				2																
Psychomyia flavida			1									1								
Psychomyiidae												2								
Pteronarcys biloba																				
Pycnopsyche guttifera		1		1								1								
Pycnopsyche lepida gr.																				
Pycnopsyche sp.													1						1	
Ranatra sp.						1														
Rheocricotopus robacki																				
Rheocricotopus sp.							1										8			
Rheotanytarsus exiguus gr.	5	6			3				3		5	42	7			2	8		2	13
Rheotanytarsus pellucidus	25						1					13	15	2		2	13		11	11
Rheotanytarsus sp.		1										3	1	2						
Rhyacophila carolina		1								1										
Rhyacophila fuscula									1			1		1						
Rhyacophila minor												5								2
Rhyacophila sp.																				
Ripistes parasita																	3	10		
Serratella serrata																3				
Serratella serratoides									3											
Serratella sp.																				
Sialis sp.																		1		
Simulium sp.	5	3		1			6		1	8	10	3		6	24	1	1			12
Simulium verecundum cplx.							1		1	1	2				1	1				1
Slavina appendiculata																	1		4	
Sperchon sp.	1		1		1							3								
Sperchonopsis sp.	1																			
Sphaerium sp.				1													3			
Sphaeromias sp.																				
Staphylinidae		1																		

Appendix B.1 continued

FinalId	SID4928	W0344	W2152	W2154	W2158	W2166	W2180	W2186	W2194	W2199	W2205	W2217	W2219	W2226	W2256	W2258	W2374	W2382	W2385	W2453
Stempellina sp.																			1	
Stempellinella sp.	1	1				9			3			2		2			1		4	1
Stenacron interpunctatum																				
Stenelmis crenata	1									3	1									14
Stenelmis sp.	17	3	16	15	1				2			14		2					5	
Stenochironomus sp.												1							1	
Stictochironomus sp.	1																			
Stylaria lacustris																		3		
Sublettea coffmani																4				
Synorthocladius sp.						1							1			1				
Tabanidae	4			1													1			
Tallaperla maria										4										
Tanypodinae		1				6						4	3					2		
Tanytarsini						1											1		1	
Tanytarsus sp.	34			5	1	20	1		11	1		1	27	10		1	3	5	57	
Teloganopsis deficiens									2					9						
Thienemanniella sp.						2						7		2		3	1			
Thienemannimyia gr.	21	1		5	7	6	1		5			3	23	6	2	2	1	3	19	9
Tipula sp.				1																
Tipulidae	1																			
Torrenticola sp.																				
Tribelos sp.		1														1				1
Trichoptera				1																
Trissopelopia sp.															1					
Trombidiformes																1				
Tropisternus sp.						1														
Tubificinae IWB											1		1				1	6	2	
Tubificinae IWH						1											2		1	
Tubificinae w capilliform setae																				
Tubificinae wo capilliform setae	15																			
Tvetenia paucunca	2	4	1	1	4		1		1	16	3	8		46						18
Tvetenia sp.												8			1					
Tvetenia vitracies		3					1		1			15					1			
Vejdovskyella comata																		2		
Xenochironomus xenolabis																				
Xylotopus par																				
Zavrelimyia sp.						2							1							
Zygoptera																				

Appendix B.2. Fish species abundances collected at each sampling site. Fish species codes are referenced from Appendix C.3.

UniqueID	AE	B	BB	BC	BND	BS	BT	CCS	CP	CRC	CS	EBT	F	FM	GS	LMB	LND	P	RBS	RP	SC	SD	SL	SMB	SS	TD	WP	WS	YB	YP	Total
B0052		1													1			2													4
B0067			1													1													2		4
B0139	1															3		4		7											15
B0143		1	2													2								1				3			9
B0157	8					3		2										9				6						19			47
B0439	12														9			4		17											42
B0440	16					1							1							4			1					1			24
B0450					16								13				1											3			33
B0575	7				88		8			4	5	3	14				11											11			151
B0612						11										4				6											21
B0650					25				4			34					4	3								2		1			73
K0001					14				1		6	12	9							6						9		64			121
K0002	2			1					1				3			1		2					1			4		2			17
SID2171					58	1					489	1	232		1	2		1										14			799
SID2507						1														5										7	13
SID2630									2				9			3	29									26		2			71
SID3026	2		6		40						25		187															16	4		280
SID3029					24		4						2															11	4		45
SID3054					3							9					5											3			20
SID4016																						1							1		2
SID4928		3			2						2	3														2		9	5		26
W0344	53							1				17								10										5	86
W2152		4	12	1												8		1	29	4									5		64
W2154			1													6				9								2	1		19
W2158											13	25	71															28	1		138
W2166			1		14			3							52			14								3		57	1		145
W2180					67																							50			117
W2186									1		1		20					1									1	1	8		33
W2194		3			5								38			1	4	12										24	6	20	113
W2199				1					1			13				1		1		1								2		12	32
W2205									1				130					4										11			146
W2217					360				1		43		57			4	36	1										52		1	555
W2219									1			49													6						56
W2226		1			65				1		3	15					20	3										17			125
W2256		3		1			48					12						3			114										181
W2258					69		1			29	13		3	17			38	1							86			11			268
W2374	25								2							1		10		2			2			7					49
W2382						3		2							1			9													15
W2385	4																			34											38
W2453		1										37													4			57			99
Total	130	17	23	4	850	20	61	8	16	33	600	230	789	17	64	37	148	85	29	105	114	7	4	1	96	53	1	471	38	45	4096

APPENDIX C:

BIOTIC TAXA CLASSIFICATIONS

Appendix C.1. Macroinvertebrate taxa with flow, thermal, and tolerance classifications. Taxa are ordered alphabetically by phylum, then class, order, family, subfamily, tribe, genus, and final ID. The final ID represents the lowest level to which each taxon was identified. Four traits of rheophily (Rheo), shape (Shp), swimming ability (Swim), and attachment (Atch) were aggregated into a flow-trait metric. Codes correspond: to Rheo1 (depositional), Rheo2 (depositional or erosional), Rheo3 (erosional); Shp1 (streamlined), Shp2 (not streamlined); Swim1 (none), Swim2 (weak), Swim3 (strong); Atch1 (none), Atch2 (some), Atch3 (both); for a flow-metric of Flow1 (no or low flow adaptation), Flow2 (some flow adaptation), Flow3 (high flow adaptation) (see Appendix C.2). Thermal codes correspond to: Ther1 (cold stenothermal or cool eurythermal), Ther2 (cool/warm eurythermal), and Ther3 (warm eurythermal). Tolerance values range 0–10 from intolerant to tolerant based on classifications developed by Massachusetts Department of Environmental Protection.

Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Annelida	Hirudinea	Pharyngobdellida	Erpobdellidae			Erpobdella	Erpobdella punctata	2	1	3	1	2	2	8
Annelida	Hirudinea	Pharyngobdellida	Erpobdellidae			Erpobdella	Erpobdella sp.	2	1	3	1	2	2	8
Annelida	Hirudinea	Rhynchobdellida	Glossiphoniidae			Helobdella	Helobdella sp.	2	1	2	1	2	3	8
Annelida	Hirudinea	Rhynchobdellida	Glossiphoniidae			Helobdella	Helobdella stagnalis	2	1	2	1	2	3	8
Annelida	Oligochaeta	Lumbricina					Lumbricina		2	2	1	1		8
Annelida	Oligochaeta	Lumbriculida	Lumbriculidae				Lumbriculidae	2	2	2	1	1		7
Annelida	Oligochaeta	Tubificida	Enchytraeidae				Enchytraeidae	1	2	2	1	1	1	10
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Dero	Dero nivea/obtusa	1	2	2	1	1		10
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae			Naidinae	1	2	2	1	1		9
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Nais	Nais behningi	1	2	2	1	1		6
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Nais	Nais communis/variabilis	1	2	2	1	1		8
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Nais	Nais elinguis	1	2	2	1	1		10
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Nais	Nais sp.	1	2	2	1	1		8
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Pristina	Pristina aequiseta	1	2	3	1	1		8
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Pristinella	Pristinella osborni	1	2	3	1	1		10
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Ripistes	Ripistes parasita	1	2	2	1	1		8
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Slavina	Slavina appendiculata	1	2	2	1	1		6
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Stylaria	Stylaria lacustris	1	2	3	1	1		8
Annelida	Oligochaeta	Tubificida	Naididae	Naidinae		Vejdovskyella	Vejdovskyella comata	1	2	2	1	1		4
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae		Aulodrilus	Aulodrilus pigueti	1	2	2	1	1		7
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae		Aulodrilus	Aulodrilus pluriseta	1	2	2	1	1		7
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae		Aulodrilus	Aulodrilus sp.	1	2	2	1	1		7
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae			Tubificinae IWB	1	2	2	1	1		10
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae			Tubificinae IWH	1	2	2	1	1		10
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae			Tubificinae w capilliform setae	1	2	2	1	1		10
Annelida	Oligochaeta	Tubificida	Naididae	Tubificinae			Tubificinae wo capilliform setae	1	2	2	1	1		10

Appendix C.1 continued

Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Arachnida	Sarcoptiformes					Oribatida							
Arthropoda	Arachnida	Trombidiformes	Hygrobatidae			Hygrobates	Hygrobates sp.	1	2	2	1	1	1	6
Arthropoda	Arachnida	Trombidiformes	Lebertiidae			Lebertia	Lebertia sp.	2	2	2	1	1	1	6
Arthropoda	Arachnida	Trombidiformes	Sperchonidae			Sperchon	Sperchon sp.	2	2	2	1	1	1	6
Arthropoda	Arachnida	Trombidiformes	Sperchonidae			Sperchonopsis	Sperchonopsis sp.	2	2	2	1	1	1	6
Arthropoda	Arachnida	Trombidiformes	Torrenticolidae			Torrenticola	Torrenticola sp.	2	2	2	1	1	1	6
Arthropoda	Arachnida	Trombidiformes					Trombidiformes	2	2	2	1	1	1	6
Arthropoda	Crustacea	Amphipoda	Crangonyctidae			Crangonyx	Crangonyx sp.	2	1	2	1	2	1	6
Arthropoda	Crustacea	Amphipoda	Gammaridae			Gammarus	Gammarus sp.	2	1	2	1	2	1	6
Arthropoda	Crustacea	Amphipoda	Hyalellidae			Hyalella	Hyalella sp.	2	1	2	1	2	1	8
Arthropoda	Crustacea	Decapoda	Cambaridae				Cambaridae	2	1	2	1	2	2	6
Arthropoda	Crustacea	Isopoda	Asellidae			Caecidotea	Caecidotea communis	2	1	1	1	2	3	8
Arthropoda	Crustacea	Isopoda	Asellidae			Caecidotea	Caecidotea sp.	2	1	1	1	2	3	8
Arthropoda	Crustacea	Ostracoda					Ostracoda	2	2	2	1	1	2	6
Arthropoda	Insecta	Coleoptera	Dytiscidae			Coptotomus	Coptotomus sp.	1	1	3	1	2		9
Arthropoda	Insecta	Coleoptera	Dytiscidae				Dytiscidae	2	1	3	1	2	2	5
Arthropoda	Insecta	Coleoptera	Dytiscidae			Neoporus	Neoporus sp.	1	2	3	1	1		5
Arthropoda	Insecta	Coleoptera	Elmidae			Ancyronyx	Ancyronyx variegata	2	2	1	1	1	2	5
Arthropoda	Insecta	Coleoptera	Elmidae			Dubiraphia	Dubiraphia sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Coleoptera	Elmidae				Elmidae	2	2	1	1	1	2	4
Arthropoda	Insecta	Coleoptera	Elmidae			Macronychus	Macronychus glabratus	2	2	1	1	1	2	5
Arthropoda	Insecta	Coleoptera	Elmidae			Microcylloepus	Microcylloepus pusillus	2	2	1	1	1	2	3
Arthropoda	Insecta	Coleoptera	Elmidae			Optioservus	Optioservus ovalis	2	2	1	1	1	2	4
Arthropoda	Insecta	Coleoptera	Elmidae			Optioservus	Optioservus sp.	2	2	1	1	1	2	4
Arthropoda	Insecta	Coleoptera	Elmidae			Optioservus	Optioservus trivittatus	2	2	1	1	1	2	4
Arthropoda	Insecta	Coleoptera	Elmidae			Oulimnius	Oulimnius latiusculus	2	2	1	1	1	1	4
Arthropoda	Insecta	Coleoptera	Elmidae			Promoresia	Promoresia sp.	2	2	1	1	1	2	2
Arthropoda	Insecta	Coleoptera	Elmidae			Promoresia	Promoresia tardella	2	2	1	1	1	1	2
Arthropoda	Insecta	Coleoptera	Elmidae			Stenelmis	Stenelmis crenata	2	2	1	1	1	3	5
Arthropoda	Insecta	Coleoptera	Elmidae			Stenelmis	Stenelmis sp.	2	2	1	1	1	3	5
Arthropoda	Insecta	Coleoptera	Gyrinidae			Dineutus	Dineutus sp.		2	3	1	1		4
Arthropoda	Insecta	Coleoptera	Gyrinidae			Gyrinus	Gyrinus sp.	1	2	3	1	1		4
Arthropoda	Insecta	Coleoptera	Hydrophilidae			Helophorus	Helophorus sp.	1	2	2	1	1		5
Arthropoda	Insecta	Coleoptera	Hydrophilidae			Tropisternus	Tropisternus sp.	1	2	2	1	1		
Arthropoda	Insecta	Coleoptera	Psephenidae			Ectopria	Ectopria nervosa	3	1	1	2	3	2	5
Arthropoda	Insecta	Coleoptera	Psephenidae			Psephenus	Psephenus herricki	3	1	1	2	3	2	4
Arthropoda	Insecta	Coleoptera	Ptilodactylidae			Anchytarsus	Anchytarsus bicolor	3	1	1	2	3	2	4
Arthropoda	Insecta	Coleoptera	Staphylinidae				Staphylinidae	1	2		1	1		5
Arthropoda	Insecta	Diptera	Athericidae			Atherix	Atherix sp.	2	2	1	1	1	2	4
Arthropoda	Insecta	Diptera	Ceratopogonidae	Ceratopogoninae			Ceratopogoninae	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Ceratopogonidae	Ceratopogoninae		Probezzia	Probezzia sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Ceratopogonidae	Ceratopogoninae		Sphaeromias	Sphaeromias sp.	2	2	1	1	1	2	
Arthropoda	Insecta	Diptera	Ceratopogonidae			Bezzia	Bezzia/Palpomyia sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Ceratopogonidae			Ceratopogon	Ceratopogon sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Ceratopogonidae				Ceratopogonidae	2	2	1	1	1	2	6

Appendix C.1 continued

Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini		Chironomini	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Chironomus	Chironomus sp.	1	2	1	1	1	2	10
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Cryptochironomus	Cryptochironomus sp.	1	2	1	1	1	2	8
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Cryptotendipes	Cryptotendipes sp.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Demicryptochironomus	Demicryptochironomus sp.	1	2	1	1	1	2	2
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Dicrotendipes	Dicrotendipes sp.	1	2	1	1	1	3	8
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Kiefferulus	Kiefferulus sp.	1	2	1	1	1	2	10
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Microtendipes	Microtendipes pedellus gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Microtendipes	Microtendipes rydalensis gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Microtendipes	Microtendipes sp.	1	2	1	1	1	2	5
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Nilothauma	Nilothauma sp.	1	2	1	1	1	3	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Paracladopelma	Paracladopelma sp.	1	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Paralauterborniella	Paralauterborniella sp.	1	2	1	1	1	2	8
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Paratendipes	Paratendipes sp.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Phaenopsectra	Phaenopsectra sp.	1	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum aviceps	1	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum fallax gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum flavum	1	2	1	1	1	3	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum halterale gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum illinoense gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum laetum	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum scalaenum	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum scalaenum gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum sp.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Polypedilum	Polypedilum tritum	1	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Stenochironomus	Stenochironomus sp.	1	2	1	1	1	3	5
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Stictochironomus	Stictochironomus sp.	1	2	1	1	1	2	9
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Tribelos	Tribelos sp.	1	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Chironomini	Xenochironomus	Xenochironomus xenolabis	1	2	1	1	1	2	0
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Cladotanytarsus	Cladotanytarsus sp.	1	2	1	1	1	2	5
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Micropsectra	Micropsectra sp.	1	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Micropsectra/Tanytarsus	Micropsectra/Tanytarsus sp.	1	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Paratanytarsus	Paratanytarsus sp.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Rheotanytarsus	Rheotanytarsus exiguus gr.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Rheotanytarsus	Rheotanytarsus pellucidus	1	2	1	1	1	2	5
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Rheotanytarsus	Rheotanytarsus sp.	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Stempellina	Stempellina sp.	1	2	1	1	1	2	2
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Stempellinella	Stempellinella sp.	1	2	1	1	1	2	2
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Subletta	Sublettea coffmani	1	2	1	1	1	2	4
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini		Tanytarsini	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae	Tanytarsini	Tanytarsus	Tanytarsus sp.	1	2	1	1	1	3	6
Arthropoda	Insecta	Diptera	Chironomidae	Chironominae			Chironominae	1	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Diamesinae		Diamesa	Diamesa sp.	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Diamesinae		Pagastia	Pagastia sp.	2	2	1	1	1	1	1
Arthropoda	Insecta	Diptera	Chironomidae	Diamesinae		Potthastia	Potthastia longimana gr.	2	2	1	1	1	1	2

Appendix C.1 continued

Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Brillia	Brillia sp.	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Cardiocladius	Cardiocladius obscurus	2	2	1	1	1	2	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Chaetocladius	Chaetocladius sp.	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Corynoneura	Corynoneura sp.	2	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Cricotopus	Cricotopus bicinctus	2	2	1	1	1	1	7
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Cricotopus	Cricotopus sp.	2	2	1	1	1	1	7
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Cricotopus	Cricotopus sylvestris	2	2	1	1	1	1	7
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Cricotopus	Cricotopus trifascia	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Cricotopus/Orthocladius	Cricotopus/Orthocladius sp.	2	2	1	1	1	1	7
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Diplocladius	Diplocladius cultriger	2	2	1	1	1	1	8
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Diplocladius	Diplocladius sp.	2	2	1	1	1	1	8
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Eukiefferiella	Eukiefferiella brehmi gr.	2	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Eukiefferiella	Eukiefferiella devonica gr.	2	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Eukiefferiella	Eukiefferiella pseudomontana gr.	2	2	1	1	1	1	8
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Eukiefferiella	Eukiefferiella sp.	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Hydrobaenus	Hydrobaenus sp.	2	2	1	1	1	1	8
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Limnophyes	Limnophyes sp.	2	2	1	1	1	1	8
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Nanocladius	Nanocladius sp.	2	2	1	1	1	1	7
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae			Orthocladiinae	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae			Orthocladiinae Sp C	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Orthocladius (Symposiocladius)	Orthocladius (Symposiocladius) lignicola	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Orthocladius	Orthocladius carlatus	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Orthocladius	Orthocladius dubitatus	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Orthocladius	Orthocladius sp.	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Parachaetocladius	Parachaetocladius sp.	2	2	1	1	1	1	2
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Paracricotopus	Paracricotopus sp.	2	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Parakiefferiella	Parakiefferiella sp.	2	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Parametriocnemus	Parametriocnemus sp.	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Paraphaenocladius	Paraphaenocladius sp.	2	2	1	1	1	1	4
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Rheocricotopus	Rheocricotopus robacki	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Rheocricotopus	Rheocricotopus sp.	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Synorthocladius	Synorthocladius sp.	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Thienemanniella	Thienemanniella sp.	2	2	1	1	1	1	6
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Tvetenia	Tvetenia paucunca	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Tvetenia	Tvetenia sp.	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Tvetenia	Tvetenia vitracies	2	2	1	1	1	3	5
Arthropoda	Insecta	Diptera	Chironomidae	Orthocladiinae		Xylotopus	Xylotopus par	2	2	1	1	1	1	7
Arthropoda	Insecta	Diptera	Chironomidae	Prodiamesinae		Odontomesa	Odontomesa sp.	2	2	1	1	1	1	5
Arthropoda	Insecta	Diptera	Chironomidae	Prodiamesinae		Prodiamesa	Prodiamesa sp.	2	2	1	1	1	1	8
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Ablabesmyia	Ablabesmyia sp.	2	2	1	1	1	3	8
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Brundiniella	Brundiniella sp.	2	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Conchapelopia	Conchapelopia sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Labrundinia	Labrundinia sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Natarsia	Natarsia sp.	2	2	1	1	1	2	8
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Nilotanypus	Nilotanypus sp.	2	2	1	1	1	3	6

Appendix C.1 continued

Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Paramerina	Paramerina sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Procladius	Procladius sp.	2	2	1	1	1	2	9
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae			Tanypodinae	2	2	1	1	1	2	7
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Thienemannimyia	Thienemannimyia gr.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Trissopelopia	Trissopelopia sp.	2	2	1	1	1	2	4
Arthropoda	Insecta	Diptera	Chironomidae	Tanypodinae		Zavrelmyia	Zavrelimyia sp.	2	2	1	1	1	2	8
Arthropoda	Insecta	Diptera	Culicidae				Culicidae	1	2	3	1	1		8
Arthropoda	Insecta	Diptera	Dixidae			Dixella	Dixella sp.	2	2	1	1	1		1
Arthropoda	Insecta	Diptera	Empididae	Clinocerinae		Clinocera	Clinocera sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Empididae	Hemerodromiinae		Chelifera	Chelifera sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Empididae	Hemerodromiinae		Hemerodromia	Hemerodromia sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Empididae	Hemerodromiinae		Neoplasta	Neoplasta sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Empididae				Empididae	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Simulidae			Simulium	Simulium sp.	3	2	1	2	2	2	5
Arthropoda	Insecta	Diptera	Simulidae			Simulium	Simulium verecundum cplx.	3	2	1	2	2	2	5
Arthropoda	Insecta	Diptera	Tabanidae				Tabanidae	1	2	1	1	1		6
Arthropoda	Insecta	Diptera	Tipulidae			Antocha	Antocha sp.	2	2	1	1	1	1	3
Arthropoda	Insecta	Diptera	Tipulidae			Dicranota	Dicranota sp.	2	2	1	1	1	1	3
Arthropoda	Insecta	Diptera	Tipulidae			Hexatoma	Hexatoma sp.	2	2	1	1	1	2	2
Arthropoda	Insecta	Diptera	Tipulidae			Pseudolimnophila	Pseudolimnophila sp.	2	2	1	1	1	2	2
Arthropoda	Insecta	Diptera	Tipulidae			Tipula	Tipula sp.	2	2	1	1	1	2	6
Arthropoda	Insecta	Diptera	Tipulidae				Tipulidae	2	2	1	1	1	2	5
Arthropoda	Insecta	Ephemeroptera	Baetidae			Acentrella	Acentrella parvula	2	1	3	1	2	1	4
Arthropoda	Insecta	Ephemeroptera	Baetidae			Acentrella	Acentrella turbida	2	1	3	1	2	1	4
Arthropoda	Insecta	Ephemeroptera	Baetidae			Acerpenna	Acerpenna macdunnoughi	2	1	3	1	2	2	5
Arthropoda	Insecta	Ephemeroptera	Baetidae			Acerpenna	Acerpenna sp.	2	1	3	1	2	2	5
Arthropoda	Insecta	Ephemeroptera	Baetidae				Baetidae	2	1	3	1	2	2	4
Arthropoda	Insecta	Ephemeroptera	Baetidae			Baetis	Baetis flavistriga	2	1	3	1	2	2	4
Arthropoda	Insecta	Ephemeroptera	Baetidae			Baetis	Baetis flavistriga/intercalaris	2	1	3	1	2	2	
Arthropoda	Insecta	Ephemeroptera	Baetidae			Baetis	Baetis intercalaris	2	1	3	1	2	3	6
Arthropoda	Insecta	Ephemeroptera	Baetidae			Baetis	Baetis pluto	2	1	3	1	2	2	6
Arthropoda	Insecta	Ephemeroptera	Baetidae			Baetis	Baetis sp.	2	1	3	1	2	2	6
Arthropoda	Insecta	Ephemeroptera	Baetidae			Baetis	Baetis tricaudatus	2	1	3	1	2	1	6
Arthropoda	Insecta	Ephemeroptera	Baetidae			Centroptilum	Centroptilum sp.	2	1	3	1	2	2	2
Arthropoda	Insecta	Ephemeroptera	Baetidae			Diphetor	Diphetor hageni	2	1	3	1	2	1	6
Arthropoda	Insecta	Ephemeroptera	Baetidae			Labiobaetis	Labiobaetis frondale	3	1	3	1	3	1	6
Arthropoda	Insecta	Ephemeroptera	Baetidae			Plauditus	Plauditus sp.		1	3	1	2	2	4
Arthropoda	Insecta	Ephemeroptera	Caenidae			Caenis	Caenis sp.	1	2	2	1	1	3	6
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Dannella	Dannella simplex	2	1		1	1	3	2
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Drunella	Drunella cornutella	2	2	2	1	1	1	0
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Ephemerella	Ephemerella sp.	2	2	2	1	1	1	1
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Ephemerella	Ephemerella subvaria	2	2	2	1	1	1	1
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Eurylophella	Eurylophella funeralis	2	2	2	1	1	1	0
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Eurylophella	Eurylophella sp.	2	2	2	1	1	1	2
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Serratella	Serratella serrata	2	2	2	1	1	2	2

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Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Serratella	Serratella serratoides	2	2	2	1	1	2	2
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Serratella	Serratella sp.	2	2	2	1	1	2	2
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae			Teloganopsis	Teloganopsis deficiens		2	2	1	1	2	2
Arthropoda	Insecta	Ephemeroptera	Heptageniidae			Epeorus	Epeorus sp.	2	1	2	1	2	1	0
Arthropoda	Insecta	Ephemeroptera	Heptageniidae				Heptageniidae	2	1	2	1	2	1	4
Arthropoda	Insecta	Ephemeroptera	Heptageniidae			Maccaffertium	Maccaffertium modestum	2	1	2	1	2	2	1
Arthropoda	Insecta	Ephemeroptera	Heptageniidae			Maccaffertium	Maccaffertium sp.	2	1	2	1	2	2	3
Arthropoda	Insecta	Ephemeroptera	Heptageniidae			Stenacron	Stenacron interpunctatum	2	1	2	1	2	3	7
Arthropoda	Insecta	Ephemeroptera	Isonychiidae			Isonychia	Isonychia bicolor	3	1	3	1	3	2	2
Arthropoda	Insecta	Ephemeroptera	Isonychiidae			Isonychia	Isonychia sp.	3	1	3	1	3	2	2
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae				Leptophlebiidae	2	1	2	1	2	3	2
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae			Paraleptophlebia	Paraleptophlebia sp.	2	1	2	1	2	1	1
Arthropoda	Insecta	Hemiptera	Corixidae				Corixidae	1	1	3	1	2	2	5
Arthropoda	Insecta	Hemiptera	Nepidae			Ranatra	Ranatra sp.	1	2	1	1	1	2	
Arthropoda	Insecta	Hemiptera	Notonectidae			Notonecta	Notonecta sp.	1	1	3	1	2		5
Arthropoda	Insecta	Hemiptera	Veliidae			Microvelia	Microvelia sp.	1	2	3	1	1	2	5
Arthropoda	Insecta	Megaloptera	Corydalidae			Chauliodes	Chauliodes rastricornis	2	2	1	1	1	2	4
Arthropoda	Insecta	Megaloptera	Corydalidae			Corydalus	Corydalus cornutus	2	2	1	1	1	2	4
Arthropoda	Insecta	Megaloptera	Corydalidae			Nigronia	Nigronia serricornis	2	2	1	1	1	2	0
Arthropoda	Insecta	Megaloptera	Corydalidae			Nigronia	Nigronia sp.	2	2	1	1	1	2	0
Arthropoda	Insecta	Megaloptera	Sialidae			Sialis	Sialis sp.	2	2	1	1	1	2	4
Arthropoda	Insecta	Odonata	Aeschnidae				Aeschnidae	2	2	3	1	2	2	3
Arthropoda	Insecta	Odonata	Aeschnidae			Boyeria	Boyeria sp.	2	2	3	1	2	2	2
Arthropoda	Insecta	Odonata	Aeschnidae			Boyeria	Boyeria vinosa	2	2	3	1	2	2	2
Arthropoda	Insecta	Odonata	Calopterygidae				Calopterygidae	2	1	2	1	2	2	5
Arthropoda	Insecta	Odonata	Calopterygidae			Calopteryx	Calopteryx sp.	2	1	2	1	2	2	6
Arthropoda	Insecta	Odonata	Coenagrionidae				Coenagrionidae	2	1	2	1	2	2	9
Arthropoda	Insecta	Odonata	Cordulegastridae			Cordulegaster	Cordulegaster sp.	1	2	2	1	1	2	3
Arthropoda	Insecta	Odonata	Corduliidae				Corduliidae	1	2	2	1	1	2	5
Arthropoda	Insecta	Odonata	Gomphidae				Gomphidae	2	2	2	1	1	2	5
Arthropoda	Insecta	Odonata	Gomphidae			Ophiogomphus	Ophiogomphus sp.	2	2	2	1	1	2	1
Arthropoda	Insecta	Odonata	Zygoptera				Zygoptera				1			6
Arthropoda	Insecta	Plecoptera	Leuctridae			Leuctra	Leuctra sp.	2	2	2	1	1	1	0
Arthropoda	Insecta	Plecoptera	Leuctridae/Capniidae				Leuctridae/Capniidae	2	2	2	1	1	1	0
Arthropoda	Insecta	Plecoptera	Peltoperlidae				Tallaperla maria	3	2	2	1	1	1	0
Arthropoda	Insecta	Plecoptera	Perlidae			Acroneuria	Acroneuria abnormis	3	1	2	1	2	2	0
Arthropoda	Insecta	Plecoptera	Perlidae			Acroneuria	Acroneuria sp.	3	1	2	1	2	2	0
Arthropoda	Insecta	Plecoptera	Perlidae			Paragnetina	Paragnetina media	3	1	2	1	2	2	5
Arthropoda	Insecta	Plecoptera	Perlidae			Paragnetina	Paragnetina sp.	3	1	2	1	2	2	1
Arthropoda	Insecta	Plecoptera	Perlidae			Perlesta	Perlesta placida	2	1	2	1	2	2	5
Arthropoda	Insecta	Plecoptera	Perlidae				Perlidae	2	1	2	1	2	2	1
Arthropoda	Insecta	Plecoptera	Perlodidae			Isoperla	Isoperla sp.	2	2	2	1	1	2	2
Arthropoda	Insecta	Plecoptera	Perlodidae				Perlodidae	2	1	2	1	2	2	2
Arthropoda	Insecta	Plecoptera	Pteronarcyidae			Pteronarcys	Pteronarcys biloba	2	2	1	1	1	1	0

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Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Insecta	Trichoptera	Apataniidae			Apatania	Apatania sp.	3	2	1	2	2	1	3
Arthropoda	Insecta	Trichoptera	Brachycentridae			Brachycentrus	Brachycentrus americanus	3	2	1	3	2	2	1
Arthropoda	Insecta	Trichoptera	Brachycentridae			Brachycentrus	Brachycentrus appalachia	3	2	1	3	2	2	0
Arthropoda	Insecta	Trichoptera	Brachycentridae			Brachycentrus	Brachycentrus numerosus	3	2	1	3	2	2	1
Arthropoda	Insecta	Trichoptera	Brachycentridae			Micrasema	Micrasema sp.	3	2	1	3	2	2	2
Arthropoda	Insecta	Trichoptera	Glossosomatidae			Glossosoma	Glossosoma sp.	3	2	1	1	1	1	0
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Cheumatopsyche	Cheumatopsyche sp.	3	2	1	2	2	2	5
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Diplectrona	Diplectrona modesta	3	2	1	2	2	1	0
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Diplectrona	Diplectrona sp.	3	2	1	2	2	1	0
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Hydropsyche	Hydropsyche betteni	3	2	1	2	2	2	7
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Hydropsyche	Hydropsyche morosa	3	2	1	2	2	2	6
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Hydropsyche	Hydropsyche morosa gr.	3	2	1	2	2	2	6
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Hydropsyche	Hydropsyche sp.	3	2	1	2	2	2	4
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Hydropsyche	Hydropsyche sparna	3	2	1	2	2	2	6
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Hydropsyche	Hydropsyche ventura	3	2	1	2	2	2	5
Arthropoda	Insecta	Trichoptera	Hydropsychidae				Hydropsychidae	3	2	1	2	2	2	4
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Macrostemum	Macrostemum sp.	3	2	1	2	2	3	3
Arthropoda	Insecta	Trichoptera	Hydropsychidae			Macrostemum	Macrostemum zebratum	3	2	1	2	2	3	3
Arthropoda	Insecta	Trichoptera	Hydroptilidae			Hydroptila	Hydroptila sp.	2	1	1	1	2	3	6
Arthropoda	Insecta	Trichoptera	Hydroptilidae			Oxyethira	Oxyethira sp.	2	1	1	2	2	2	3
Arthropoda	Insecta	Trichoptera	Lepidostomatidae			Lepidostoma	Lepidostoma sp.	2	2	1	1	1	1	1
Arthropoda	Insecta	Trichoptera	Leptoceridae			Ceraclea	Ceraclea sp.	2	2	2	2	2	2	3
Arthropoda	Insecta	Trichoptera	Leptoceridae				Leptoceridae	2	2	2	2	2	2	4
Arthropoda	Insecta	Trichoptera	Leptoceridae			Mystacides	Mystacides sepulchralis	2	2	2	2	2	2	4
Arthropoda	Insecta	Trichoptera	Leptoceridae			Oecetis	Oecetis persimilis	2	2	2	2	2	3	5
Arthropoda	Insecta	Trichoptera	Leptoceridae			Oecetis	Oecetis sp.	2	2	2	2	2	3	5
Arthropoda	Insecta	Trichoptera	Limnephilidae			Goera	Goera sp.	2	2	1	2	2	2	3
Arthropoda	Insecta	Trichoptera	Limnephilidae				Limnephilidae	2	2	1	2	2	2	4
Arthropoda	Insecta	Trichoptera	Limnephilidae			Platycentropus	Platycentropus sp.	1	2	1	2	1	2	4
Arthropoda	Insecta	Trichoptera	Limnephilidae			Pycnopsyche	Pycnopsyche guttifera	2	2	1	2	2	1	4
Arthropoda	Insecta	Trichoptera	Limnephilidae			Pycnopsyche	Pycnopsyche lepida gr.	2	2	1	2	2	1	
Arthropoda	Insecta	Trichoptera	Limnephilidae			Pycnopsyche	Pycnopsyche sp.	2	2	1	2	2	1	4
Arthropoda	Insecta	Trichoptera	Molannidae			Molanna	Molanna sp.		2	1	2	1		6
Arthropoda	Insecta	Trichoptera	Odontoceridae			Psilotreta	Psilotreta frontalis	2	2	1	2	2	1	0
Arthropoda	Insecta	Trichoptera	Philopotamidae			Chimarra	Chimarra aterrima	3	2	1	2	2	3	4
Arthropoda	Insecta	Trichoptera	Philopotamidae			Chimarra	Chimarra obscura	3	2	1	2	2	3	4
Arthropoda	Insecta	Trichoptera	Philopotamidae			Chimarra	Chimarra sp.	3	2	1	2	2	3	4
Arthropoda	Insecta	Trichoptera	Philopotamidae			Dolophilodes	Dolophilodes distinctus	3	2	1	2	2	1	0
Arthropoda	Insecta	Trichoptera	Philopotamidae			Dolophilodes	Dolophilodes sp.	3	2	1	2	2	1	0
Arthropoda	Insecta	Trichoptera	Philoptamidae				Philopotamidae	3	2	1	2	2	2	3
Arthropoda	Insecta	Trichoptera	Polycentropodidae			Nyctiophylax	Nyctiophylax sp.	2	2	1	2	2	2	5
Arthropoda	Insecta	Trichoptera	Polycentropodidae			Phylocentropus	Phylocentropus sp.	1	2	1	2	1	2	5
Arthropoda	Insecta	Trichoptera	Polycentropodidae			Polycentropus	Polycentropus sp.	3	2	1	2	2	2	6
Arthropoda	Insecta	Trichoptera	Psychomyiidae			Lype	Lype diversa	3	2	1	2	2	2	2
Arthropoda	Insecta	Trichoptera	Psychomyiidae			Psychomyia	Psychomyia flavida	3	2	1	2	2	2	2

Appendix C.1 continued

Phylum	Class	Order	Family	Subfamily	Tribe	Genus	FinalId	Rheo	Shpe	Swim	Atch	Flow	Ther	Tol
Arthropoda	Insecta	Trichoptera	Psychomyiidae				Psychomyiidae	3	2	1	2	2	2	2
Arthropoda	Insecta	Trichoptera	Rhyacophilidae			Rhyacophilia	Rhyacophila carolina	3	2	2	2	2	1	1
Arthropoda	Insecta	Trichoptera	Rhyacophilidae			Rhyacophilia	Rhyacophila fuscula	3	2	2	2	2	1	0
Arthropoda	Insecta	Trichoptera	Rhyacophilidae			Rhyacophilia	Rhyacophila minor	3	2	2	2	2	1	1
Arthropoda	Insecta	Trichoptera	Rhyacophilidae			Rhyacophilia	Rhyacophila sp.	3	2	2	2	2	1	1
Arthropoda	Insecta	Trichoptera	Uenoidae			Neophylax	Neophylax oligius	3	2	2	2	2	2	3
Arthropoda	Insecta	Trichoptera					Trichoptera	2	2	2	3	2	2	4
Mollusca	Gastropoda	Basommatophora	Ancylidae				Ancylidae	2	1	1	2	2		6
Mollusca	Gastropoda	Basommatophora	Ancylidae			Ferrissia	Ferrissia sp.	3	1	1	2	3		6
Mollusca	Gastropoda	Basommatophora	Lymnaeidae				Lymnaeidae	2	2	1	2	2		6
Mollusca	Gastropoda	Basommatophora	Physidae			Physa	Physa sp.	2	2	1	2	2	3	9
Mollusca	Gastropoda	Basommatophora	Physidae				Physidae	2	2	1	2	2		8
Mollusca	Gastropoda	Basommatophora	Planorbidae			Gyraulus	Gyraulus parvus		2	1	2	1		8
Mollusca	Gastropoda	Basommatophora	Planorbidae			Menetus	Menetus dilatatus		2	1	2	1		6
Mollusca	Gastropoda	Basommatophora	Planorbidae			Planorbella	Planorbella sp.		2	1	2	1		6
Mollusca	Gastropoda	Basommatophora	Planorbidae				Planorbidae	2	2	1	2	2		6
Mollusca	Gastropoda	Mesogastropoda	Hydrobiidae			Amnicola	Amnicola sp.	2	2	1	2	2	3	5
Mollusca	Gastropoda	Mesogastropoda	Hydrobiidae				Hydrobiidae	2	2	1	2	2	3	8
Mollusca	Pelecypoda	Veneroida	Corbiculidae			Corbicula	Corbicula fluminea	3	1	1	2	3		6
Mollusca	Pelecypoda	Veneroida	Pisidiidae				Pisidiidae	2	1	1	2	2		6
Mollusca	Pelecypoda	Veneroida	Pisidiidae			Pisidium	Pisidium sp.	1	1	1	2	2	2	6
Mollusca	Pelecypoda	Veneroida	Pisidiidae			Sphaerium	Sphaerium sp.		1	1	2	2	3	6
Nemata							Nemata			1	2	1		

Appendix C.2. Macroinvertebrate traits for rheophily, shape, swimming ability, and attachment were used to categorize taxa into categories of high-flow adaptation, some-flow adaptation, and low- or no-flow adaptation. The trait codes in parentheses refer to the categories referenced in Appendix C.1 and established by Poff et al. (2006b).

	Trait			
Flow adaptation	Rheophily	Shape	Swimming	Attachment
High (3)	Erosional (3)	Streamlined (1)	Strong (3)	None (1)
	Erosional (3)	Streamlined (1)	None (1)	Some (2)
Some (2)	Erosional (3)	Streamlined (1)	Weak (2)	None (1)
	Erosional (3)	Not streamlined (2)	Weak (2)	Some (2)
	Erosional (3)	Not streamlined (2)	None (1)	Some or none (3)
	Erosional (3)	Not streamlined (2)	None (1)	Some (2)
	Erosional or depositional (2)	Streamlined (1)	Strong (3)	None (1)
	Erosional or depositional (2)	Streamlined (1)	Weak (2)	None (1)
	Erosional or depositional (2)	Streamlined (1)	None (1)	Some (2)
	Erosional or depositional (2)	Not streamlined (2)	Strong (3)	None (1)
	Erosional or depositional (2)	Not streamlined (2)	Weak (2)	Some or none (3)
	Erosional or depositional (2)	Not streamlined (2)	None (1)	Some (2)
	Depositional (1)	Streamlined (1)	Strong (3)	None (1)
	Depositional (1)	Streamlined (1)	None (1)	Some (2)
Low/no (1)	Erosional (3)	Not streamlined (2)	Weak (2)	None (1)
	Erosional (3)	Not streamlined (2)	None (1)	None (1)
	Erosional or depositional (2)	Not streamlined (2)	Weak (2)	None (1)
	Erosional or depositional (2)	Not streamlined (2)	None (1)	None (1)
	Depositional (1)	Not streamlined (2)	Strong (3)	None (1)
	Depositional (1)	Not streamlined (2)	Weak (2)	None (1)
	Depositional (1)	Not streamlined (2)	None (1)	Some (2)
	Depositional (1)	Not streamlined (2)	None (1)	None (1)
	Not listed	Not streamlined (2)	None (1)	Some (2)

Appendix C.3. Fish classifications used for flow, thermal, and tolerance response variables (Kashiwagi and Richards 2009, Armstrong et al. 2011). Flow codes represent FD (fluvial dependent), FS (fluvial specialist), and MG (macrohabitat generalist). FD and FS were combined into one response variable for fluvial fishes. Thermal codes represent COLD (coldwater), COOL (coolwater), and WARM (warmwater). Tolerance codes represent INTOL (intolerant), INTER (intermediate), and TOL (tolerant).

Family	Fish Code	Scientific name	Common name	Flow	Thermal	Tolerance
Anguillidae						
	AE	*Anguilla rostrata*	American eel	MG	WARM	TOL
Catostomidae						
	WS	*Catostomus commersoni*	White sucker	FD	COOL	TOL
	CCS	*Erimyzon oblongus*	Creek chubsucker	FS	WARM	INTOL
Centrarchidae						
	BS	*Enneacanthus obesus*	Banded sunfish	MG	WARM	INTER
	RBS	*Lepomis auritis*	Redbreast sunfish	MG	WARM	INTER
	P	*Lepomis gibbosus*	Pumpkinseed	MG	WARM	INTER
	B	*Lepomis macrochirus*	Bluegill	MG	WARM	TOL
	SMB	*Micropterus dolomieu*	Smallmouth bass	MG	WARM	INTER
	LMB	*Micropterus salmoides*	Largemouth bass	MG	WARM	INTER
	BC	*Pomoxis nigromaculatus*	Black crappie	MG	WARM	INTER
Cottidae						
	SC	*Cottus cognatus*	Slimy sculpin	FS	COLD	INTOL
Cyprinidae						
	CS	*Luxillus cornutus*	Common shiner	FD	WARM	INTER
	GS	*Notemigonus crysoleucas*	Golden shiner	MG	WARM	TOL
	SS	*Notropis hudsonius*	Spottail shiner	MG	WARM	INTER
	FM	*Pimephales promelas*	Fathead minnow	MG	WARM	TOL
	BND	*Rhinichthys atratulus*	Blacknose dace	FS	COOL	TOL
	LND	*Rhinichthys cataractae*	Longnose dace	FS	COOL	INTER
	CRC	*Semotilus atromaculatus*	Creek chub	FS	COOL	TOL
	F	*Semotilus corporalis*	Fallfish	FS	COLD	INTER
Esocidae						
	RP	*Esox americanus*	Redfin pickerel	MG	WARM	INTER
	CP	*Esox niger*	Chain pickerel	MG	WARM	INTER
Ictaluridae						
	YB	*Ameiurus natalis*	Yellow bullhead	MG	WARM	TOL
	BB	*Ameiurus nebulosus*	Brown bullhead	MG	WARM	TOL
Moronidae						
	WP	*Morone americana*	White perch	MG	WARM	INTER
Percidae						
	SD	*Etheostoma fusiforme*	Swamp darter	MG	WARM	INTOL
	TD	*Etheostoma olmstedi*	Tesselated darter	FS	WARM	INTER
	YP	*Perca flavescens*	Yellow perch	MG	WARM	INTER
Petromyzontidae						
	SL	*Petromyzon marinus*	Sea lamprey	FD	COOL	INTER
Salmonidae						
	BT	*Salmo trutta*	Brown trout	FS	COLD	INTOL
	EBT	*Salvelinus fontinalis*	Brook trout	FS	COLD	INTOL

APPENDIX D:

BIOTIC RESPONSE METRICS
CALCULATED FROM RAW DATA

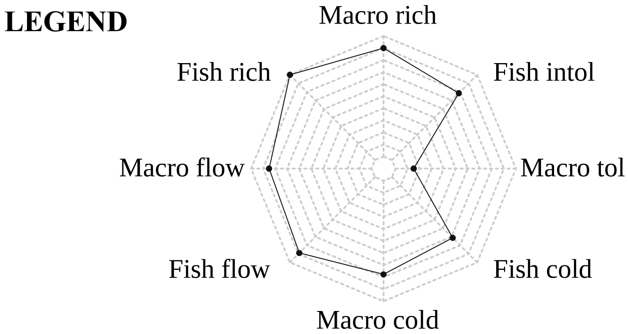
Appendix D. Biotic response metrics calculated from macroinvertebrate and fish sampling at each site. Taxa abundances are from Appendix B; flow, thermal, and tolerance classifications are from Appendix C.

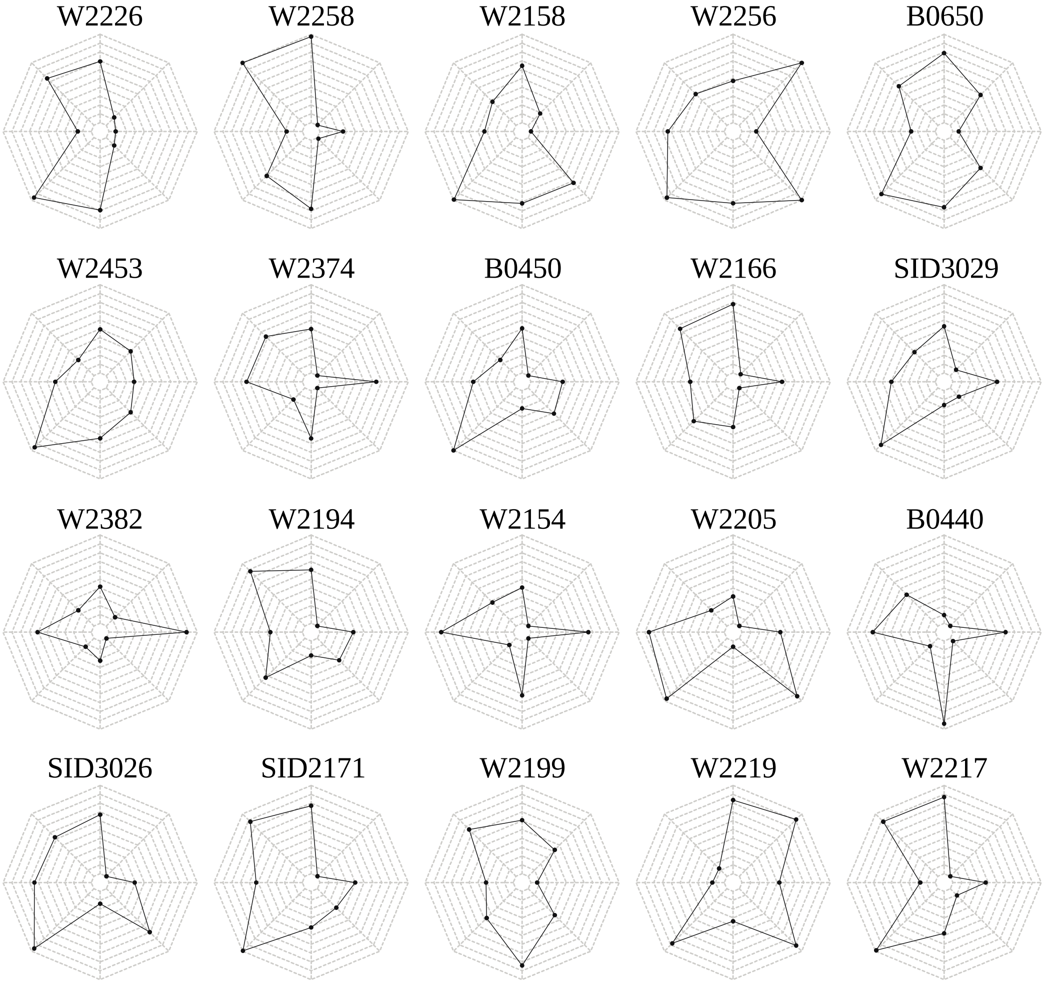
	Richness		Flow traits (%)		Thermal traits (%)		Tolerance	
UniqueID	Macro	Fish	Macro	Fish	Macro	Fish	Macro	Fish (%)
B0052	26	3	31.8	0.0	29.1	0.0	4.9	0.0
B0067	16	3	84.1	0.0	16.8	0.0	5.3	0.0
B0139	23	4	35.3	0.0	52.0	0.0	3.6	0.0
B0143	20	5	80.4	33.3	3.7	0.0	4.7	0.0
B0157	27	6	43.1	44.7	19.6	0.0	4.4	17.0
B0439	22	4	15.8	0.0	13.7	0.0	7.1	0.0
B0440	12	6	72.0	12.5	59.0	4.2	6.0	0.0
B0450	26	4	51.0	100.0	13.5	39.4	4.9	0.0
B0575	30	9	75.5	95.4	21.7	16.6	4.8	7.3
B0612	22	3	43.1	0.0	40.2	0.0	4.6	0.0
B0650	35	7	36.0	90.4	48.0	46.6	3.7	46.6
K0001	42	8	22.5	94.2	20.5	17.4	5.4	9.9
K0002	38	9	13.5	58.8	16.3	17.6	5.9	0.0
SID2171	34	9	56.7	99.4	26.3	29.2	5.1	0.1
SID2507	13	3	90.8	0.0	62.9	0.0	7.7	0.0
SID2630	27	6	64.9	93.0	19.7	12.7	4.6	0.0
SID3026	31	7	66.8	95.7	9.7	66.8	4.6	0.0
SID3029	26	5	54.6	91.1	11.1	13.3	5.5	8.9
SID3054	24	4	44.7	100.0	45.0	45.0	4.5	45.0
SID4016	22	2	68.1	0.0	18.5	0.0	5.1	50.0
SID4928	35	7	18.9	69.2	23.1	11.5	5.5	11.5
W0344	32	5	16.6	20.9	27.8	19.8	5.1	20.9
W2152	22	8	65.7	0.0	5.9	0.0	5.0	0.0
W2154	22	5	81.0	10.5	39.2	0.0	6.2	0.0
W2158	30	5	40.6	99.3	45.3	69.6	3.4	18.1
W2166	35	8	45.4	53.1	26.5	0.0	5.3	2.1
W2180	26	2	79.1	100.0	10.9	0.0	5.3	0.0
W2186	9	7	96.1	66.7	1.0	60.6	5.6	0.0
W2194	29	9	43.4	62.8	11.1	33.6	5.0	0.0
W2199	29	8	39.0	46.9	53.0	40.6	3.7	40.6
W2205	19	4	84.0	96.6	5.0	89.0	5.3	0.0
W2217	38	9	27.6	98.7	30.4	10.3	5.0	0.0
W2219	37	3	24.7	87.5	22.0	87.5	5.2	87.5
W2226	32	8	26.2	96.0	50.0	12.0	3.7	12.0
W2256	25	6	66.3	96.1	45.2	96.1	4.1	96.1
W2258	41	10	28.2	61.2	49.1	1.5	4.5	0.4
W2374	25	7	65.7	18.4	34.6	0.0	6.1	0.0
W2382	23	4	63.8	13.3	14.8	0.0	7.2	13.3
W2385	25	2	24.1	0.0	10.5	0.0	6.0	0.0
W2453	25	4	47.2	94.9	34.5	37.4	4.6	37.4

APPENDIX E:

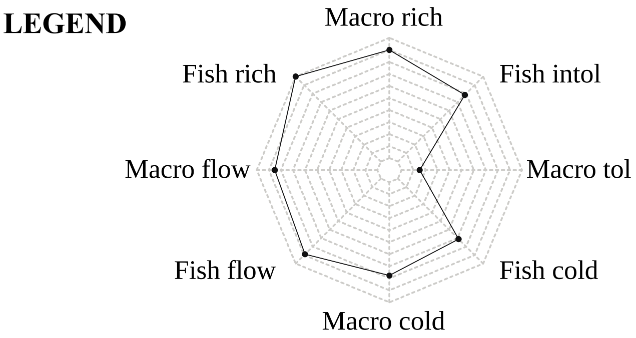
BIOTIC RESPONSE SPIDER PLOTS

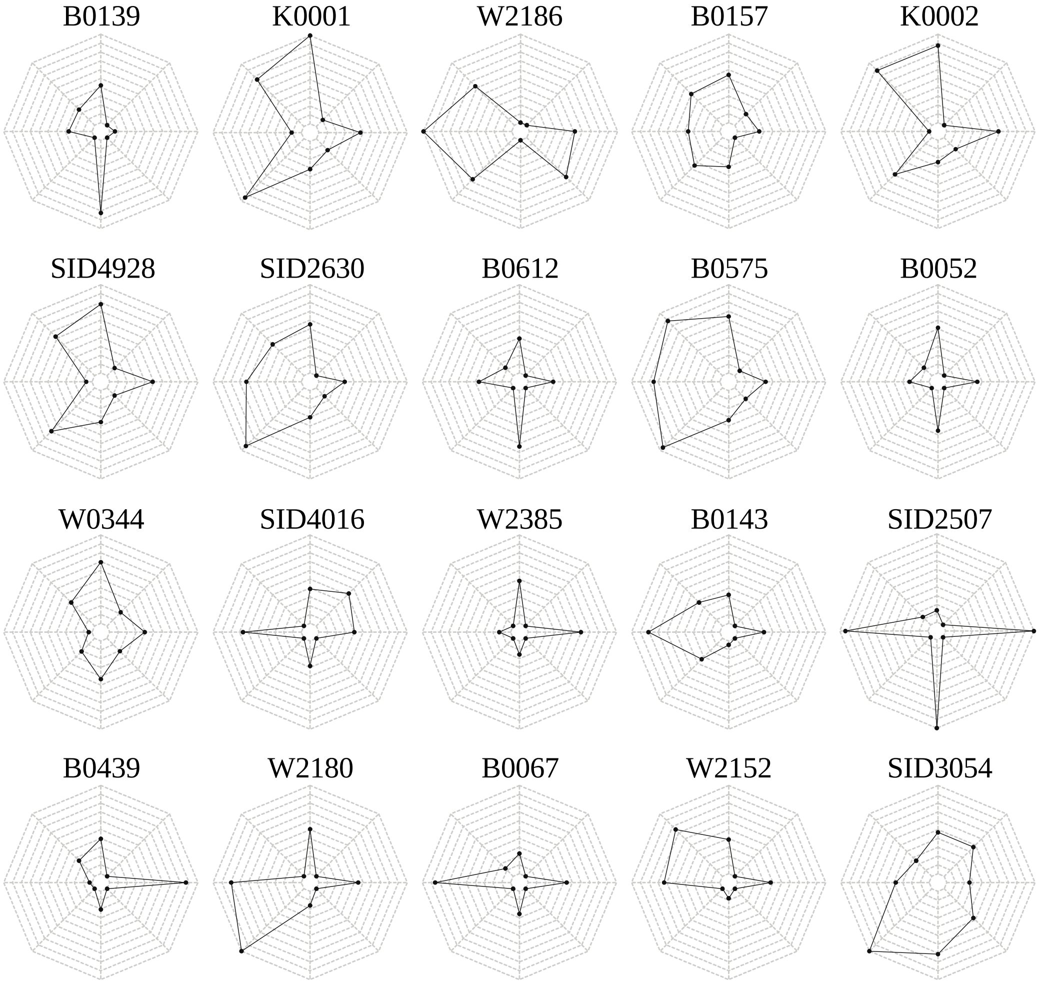
Appendix E.1. Spider plots showing response variables for sites within the very-low band, arranged from lowest to highest percent impervious cover (left to right, then top to bottom). Response metrics are: macroinvertebrate richness (macro rich), fish richness (fish rich), macroinvertebrate flow traits (macro flow), fish flow traits (fish flow), macroinvertebrate thermal traits (macro cold), fish thermal traits (fish cold), macroinvertebrate tolerance index (macro tol), and fish intolerance (fish intol).





Appendix E.2. Spider plots showing response variables for sites within the low band, arranged from lowest to highest percent impervious cover (left to right, then top to bottom). Response metrics are: macroinvertebrate richness (macro rich), fish richness (fish rich), macroinvertebrate flow traits (macro flow), fish flow traits (fish flow), macroinvertebrate thermal traits (macro cold), fish thermal traits (fish cold), macroinvertebrate tolerance index (macro tol), and fish intolerance (fish intol).





APPENDIX F:

REACH-SCALE VARIABLES AND CODES

Appendix F.1 Reach codes and descriptions for each predictor category of habitat, flow, temperature, and water quality.

Category	Code	Description	Units
Habitat			
	AREA.BF.mean	Bankfull area, mean	m2
	AREA.BF.cv	Bankfull area, cv	unitless
	WIDTH.BF.mean	Bankfull width, mean	m
	WIDTH.BF.cv	Bankfull width, cv	unitless
	TWP	Pool habitat	% of reach
	TWRF	Riffle habitat	% of reach
	Hab.trans	Habitat unit transitions	number
	Sed.D16	Sediment, D16	mm
	Sed.D50	Sediment, D50	mm
	Sed.D84	Sediment, D84	mm
	Sed.het	Sediment, heterogeneity	unitless
	Sed.sorting	Sediment, gradation coefficient	unitless
	Sed.SD	Sediment, sorting	unitless
	Embed.avg	Embeddedness	%
	Banks.veg	Banks, vegetated	% of reach
	Banks.erode	Banks, eroded	% of reach
	Banks.cut	Banks, undercut	%
	Banks.dep	Depositional features	% of reach
	LWD.volume	Large wood, volume	
Flow			
	Slope	Slope	
	W.D.RATIO.mean	Width:depth ratio, mean	unitless
	W.D.RATIO.cv	Width:depth ratio, cv	unitless
	ENTRENCH.mean	Entrenchment, mean	unitless
	ENTRENCH.cv	Entrenchment, cv	unitless
	Power.width	Stream power	

Category	Code	Description	Units
Temperature			
	Temp.Avg.summ.mean	Mean summer daily mean temp	°C
	Temp.Max.summ.mean	Max summer daily mean temp	°C
	Temp.Avg.summ.min	Mean summer daily min temp	°C
	Temp.Avg.summ.max	Mean summer daily max temp	°C
	Temp.Avg.summ.range	Mean summer daily temp range	°C
	Canopy	Canopy cover	%
	Riparian.basal	Riparian vegetation	
Water quality			
	DO.min	Dissolved oxygen, min	mg/L
	DO.mean	Dissolved oxygen, mean	mg/L
	DO.cv	Dissolved oxygen, cv	unitless
	Cond.max	Specific conductance, max	µS/cm
	Cond.mean	Specific conductance, mean	µS/cm
	Cond.cv	Specific conductance, cv	unitless
	Nitrate.max	Nitrate, max	mg/L
	Nitrate.mean	Nitrate, mean	mg/L
	Nitrate.cv	Nitrate, cv	unitless

Appendix F.2. Reach-scale variables for each site within the habitat predictor category. Codes are referenced in Appendix F.1.

UniqueID	AREA.BF. mean	AREA.BF. cv	WIDTH.BF. mean	WIDTH.BF. cv	TWP	TWRF	Hab.trans	Sed.D16	Sed.D50	Sed.D84	Sed.het	Sed.SD	Sed.sorting	Embed.avg	Banks.veg	Banks.erode	Banks.cut	Banks.dep	LWD. volume
B0052	2.32	0.24	6.07	0.22	0.00	11.50	6	4.0	29.0	89.4	3.08	2.24	5.17	25.71	50.75	39.00	12.50	0.00	0.65
B0067	5.40	0.14	6.68	0.10	0.00	0.00	0	1.0	1.0	2.7	2.72	0.68	1.86	10.48	74.63	62.88	37.50	4.50	0.13
B0139	1.60	0.29	4.45	0.29	0.00	42.69	9	4.0	28.0	60.0	2.14	1.95	4.57	24.76	49.25	23.25	17.50	0.00	0.98
B0143	3.26	0.46	8.32	0.51	2.87	31.40	11	2.6	19.0	69.4	3.65	2.37	5.43	23.10	45.25	54.75	25.00	13.25	5.04
B0157	4.67	0.43	9.36	0.32	0.00	15.83	6	2.0	13.0	53.0	4.08	2.36	5.29	20.48	48.38	26.50	30.00	0.00	0.99
B0439	6.37	0.13	8.59	0.08	43.96	0.00	6	1.0	4.0	34.1	8.52	2.54	6.26	5.95	93.13	7.75	0.00	0.00	0.81
B0440	1.41	0.34	4.83	0.33	6.29	60.08	10	6.0	30.0	78.4	2.61	1.85	3.81	14.29	50.00	49.00	30.00	24.75	0.85
B0450	3.21	0.39	6.51	0.26	4.90	44.22	14	56.3	104.0	265.0	2.55	1.12	2.20	1.82	33.81	16.79	14.29	0.00	1.54
B0575	1.99	0.41	5.01	0.30	23.95	29.63	11	2.0	15.0	45.4	3.02	2.25	5.26	30.00	41.88	29.75	2.50	14.63	1.38
B0612	1.57	0.23	3.54	0.12	0.00	15.80	4	4.0	36.0	85.0	2.36	2.20	5.68	23.33	53.00	79.50	80.00	0.00	0.46
B0650	7.73	0.16	11.40	0.37	0.00	0.00	0	2.0	4.0	27.1	6.77	1.88	4.39	10.71	69.50	27.50	7.50	0.00	0.67
K0001	3.98	0.10	9.37	0.16	5.94	0.00	2	1.0	1.0	1.0	1.00	0.00	1.00	3.81	64.13	71.50	7.50	55.25	1.66
K0002	7.51	0.24	8.25	0.10	57.01	0.00	9	1.0	1.0	2.0	2.00	0.50	1.50	0.95	45.75	74.00	32.50	35.00	2.54
SID2171	2.95	0.20	6.81	0.19	6.60	32.94	5	2.0	4.0	24.1	6.02	1.79	4.01	24.25	65.63	66.75	27.50	6.25	0.73
SID2507	1.39	0.53	3.28	0.39	0.00	0.00	0	1.0	1.0	1.0	1.00	0.00	1.00	15.71	78.00	67.00	37.50	7.25	0.00
SID2630	5.41	0.21	10.20	0.11	10.65	15.81	7	9.3	40.0	91.8	2.30	1.66	3.30	30.95	53.75	59.25	36.67	38.33	1.47
SID3026	4.96	0.20	11.02	0.03	2.32	57.04	10	4.0	85.0	241.8	2.84	2.96	12.05	46.67	35.63	46.38	27.50	18.75	0.83
SID3029	4.38	0.64	9.36	0.35	11.34	64.88	12	11.3	121.5	266.8	2.20	2.28	6.46	4.76	17.00	17.13	7.50	24.25	0.79
SID3054	2.35	0.21	6.13	0.27	3.07	93.11	3	7.0	72.0	161.7	2.25	2.26	6.24	27.71	47.05	30.91	45.00	2.50	0.39
SID4016	2.26	0.60	6.40	0.30	44.73	41.14	8	3.3	40.0	86.2	2.15	2.39	7.17	10.48	59.75	43.00	17.50	38.75	1.33
SID4928	1.66	0.25	4.97	0.22	0.00	0.00	6	1.0	1.0	2.0	2.00	0.50	1.50	0.71	54.25	51.00	27.50	30.50	0.06
W0344	4.47	0.19	9.93	0.18	12.72	3.99	11	7.6	29.0	75.4	2.60	1.65	3.20	14.05	64.75	38.63	45.00	26.00	5.43
W2152	2.80	0.44	7.73	0.34	16.40	37.74	8	4.0	34.0	83.4	2.45	2.19	5.48	26.90	52.88	48.88	32.50	28.50	0.61
W2154	2.17	0.24	7.45	0.34	0.00	2.66	2	1.0	1.0	31.4	31.36	2.49	16.18	4.52	45.63	69.13	22.50	67.25	0.49
W2158	3.60	0.33	7.74	0.26	18.79	19.07	10	2.0	49.0	121.4	2.48	2.96	13.49	16.19	49.00	69.75	75.00	0.00	49.78
W2166	0.89	0.38	3.11	0.19	8.91	4.05	5	2.6	7.0	19.4	2.77	1.45	2.71	0.95	82.50	20.75	17.50	7.25	0.58
W2180	3.23	0.32	7.57	0.36	32.22	27.21	9	2.0	29.0	91.4	3.15	2.76	8.83	25.24	55.88	49.25	15.00	4.25	0.10
W2186	2.39	0.67	7.24	0.24	36.21	63.79	4	42.0	67.0	108.0	1.61	0.68	1.60	3.10	50.25	38.75	25.00	24.75	8.19
W2194	8.37	0.36	14.67	0.24	59.23	25.70	8	18.4	50.0	95.6	1.91	1.19	2.31	10.97	70.31	27.73	27.50	20.75	18.98
W2199	3.88	0.34	8.84	0.24	8.81	72.26	4	2.0	180.0	350.7	1.95	3.73	45.97	54.05	49.13	20.75	85.00	10.00	1.95
W2205	2.60	0.14	6.22	0.11	57.65	5.88	8	4.0	25.0	85.4	3.42	2.21	4.83	9.29	36.88	69.13	67.50	34.50	7.13
W2217	1.07	0.62	3.11	0.33	38.38	37.06	7	1.0	12.0	54.4	4.53	2.88	8.27	10.48	71.50	28.50	10.00	15.25	0.47
W2219	3.30	0.21	5.39	0.18	0.00	0.00	0	1.0	1.0	1.0	1.00	0.00	1.00	0.00	31.38	83.75	87.50	1.00	23.34
W2226	2.71	0.31	7.06	0.24	13.20	61.20	8	7.6	67.0	126.0	1.88	2.02	5.33	11.67	45.38	26.50	67.50	23.50	4.33
W2256	3.42	0.24	9.06	0.15	11.82	88.18	4	30.6	54.0	87.4	1.62	0.76	1.69	8.10	70.00	31.88	15.00	41.75	28.42
W2258	9.54	0.18	13.17	0.11	0.00	57.82	3	2.0	20.0	72.3	3.62	2.59	6.81	17.20	68.02	52.40	5.00	25.00	1.15
W2374	5.37	0.31	9.45	0.26	57.40	0.00	10	1.0	1.0	2.0	2.00	0.50	1.50	0.00	54.63	57.25	52.50	14.00	0.76
W2382	4.27	0.12	5.86	0.08	0.00	0.00	0	1.0	1.0	1.0	1.00	0.00	1.00	0.00	60.00	70.75	0.00	0.00	0.00
W2385	3.57	0.23	7.52	0.10	5.31	0.00	2	1.0	2.0	12.0	6.00	1.79	4.00	20.00	38.75	27.00	0.00	0.00	0.67
W2453	2.37	0.29	5.89	0.30	70.68	15.56	13	2.0	2.0	15.4	7.68	1.47	4.34	10.00	50.63	44.50	67.50	38.75	1.71

Appendix F.3. Reach-scale variables for each site within the flow predictor category. Codes are referenced in Appendix F.1.

UniqueID	Slope	W.D.RATIO. mean	W.D.RATIO. cv	ENTRENCH. mean	ENTRENCH. cv	Power.width
B0052	0.01	16.11	0.27	3.33	0.16	41.06
B0067	0.00	8.28	0.07	4.28	0.08	0.98
B0139	0.01	12.46	0.30	2.41	0.42	97.01
B0143	0.01	22.15	0.60	2.86	0.16	84.99
B0157	0.00	19.59	0.35	3.12	0.27	27.28
B0439	0.00	11.73	0.16	3.68	0.14	11.23
B0440	0.01	17.31	0.43	2.70	0.24	79.62
B0450	0.03	13.85	0.33	3.54	0.36	283.24
B0575	0.01	12.81	0.29	2.32	0.55	124.95
B0612	0.00	8.11	0.10	2.02	0.17	52.84
B0650	0.00	17.44	0.59	4.30	0.59	2.82
K0001	0.00	22.84	0.35	3.36	0.21	1.61
K0002	0.00	9.46	0.29	3.52	0.46	29.98
SID2171	0.00	16.22	0.32	2.70	0.20	30.08
SID2507	0.00	8.03	0.30	4.87	0.30	11.39
SID2630	0.00	19.92	0.27	1.28	0.09	54.76
SID3026	0.01	25.16	0.17	1.89	0.23	151.68
SID3029	0.04	21.58	0.31	2.16	0.31	421.81
SID3054	0.02	16.14	0.35	2.25	0.30	200.15
SID4016	0.01	19.60	0.19	2.17	0.15	47.69
SID4928	0.00	16.11	0.44	3.35	0.58	8.32
W0344	0.00	22.82	0.33	3.43	0.44	28.16
W2152	0.00	22.31	0.37	3.84	0.53	41.40
W2154	0.00	26.16	0.51	2.74	0.40	11.84
W2158	0.01	16.90	0.25	1.96	0.28	71.69
W2166	0.00	12.07	0.50	5.57	0.38	19.84
W2180	0.00	20.23	0.64	1.70	0.20	45.30
W2186	0.01	27.29	0.58	1.84	0.61	161.85
W2194	0.01	29.26	0.59	2.87	0.37	57.43
W2199	0.02	21.18	0.36	2.19	0.31	60.78
W2205	0.01	15.01	0.15	2.00	0.28	67.11
W2217	0.01	11.38	0.49	3.38	0.20	126.04
W2219	0.00	9.15	0.33	4.45	0.21	11.16
W2226	0.02	18.89	0.30	2.23	0.24	214.12
W2256	0.01	25.03	0.27	1.65	0.38	114.14
W2258	0.01	18.46	0.19	1.89	0.27	73.46
W2374	0.00	16.71	0.24	3.38	0.17	4.53
W2382	0.00	8.16	0.17	2.14	0.40	2.87
W2385	0.00	16.23	0.19	2.89	0.09	2.49
W2453	0.01	14.70	0.32	2.85	0.07	34.29

Appendix F.4. Reach-scale variables for each site within the temperature predictor category. Codes are referenced in Appendix F.1.

UniqueID	Temp.Avg. summ.mean	Temp.Max. summ.mean	Temp.Avg. summ.min	Temp.Avg. summ.max	Temp.Avg. summ.range	Canopy	Riparian. basal
B0052	19.63	26.34	18.31	21.13	2.82	64.78	23.61
B0067	24.26	27.83	22.86	25.75	2.89	0.35	0.67
B0139	20.84	24.88	19.85	21.96	2.11	81.58	25.06
B0143	23.56	27.34	22.43	24.89	2.46	81.79	27.31
B0157	19.07	23.25	17.86	20.37	2.51	68.63	42.63
B0439	22.32	25.08	20.97	23.75	2.78	30.46	11.05
B0440	18.65	21.59	17.10	20.20	3.10	87.39	17.59
B0450	21.49	25.61	20.04	23.18	3.14	88.30	55.31
B0575	20.34	23.93	18.53	22.25	3.72	55.81	7.78
B0612	18.52	22.68	17.13	19.96	2.83	91.60	30.93
B0650	18.35	22.85	16.87	19.83	2.96	26.12	18.56
K0001	19.30	23.63	17.52	21.02	3.50	52.66	18.71
K0002	21.72	25.60	20.73	22.84	2.11	76.68	38.09
SID2171	20.11	22.77	18.92	21.50	2.58	77.66	28.95
SID2507	22.95	26.60	19.82	26.45	6.63	33.68	7.99
SID2630	21.83	25.77	20.74	23.05	2.31	75.98	25.73
SID3026	23.05	25.82	21.39	25.14	3.75	94.26	46.12
SID3029	21.37	26.63	20.45	22.40	1.96	93.91	42.03
SID3054	18.45	25.67	17.29	19.65	2.36	82.78	38.94
SID4016	19.53	23.06	17.85	21.39	3.55	83.89	20.42
SID4928	18.44	22.00	16.76	20.19	3.42	88.31	15.68
W0344	19.99	25.56	18.55	21.56	3.01	82.63	37.78
W2152	20.17	25.18	19.04	21.43	2.39	69.19	21.92
W2154	19.15	22.80	17.49	20.87	3.39	66.25	13.92
W2158	19.73	23.40	18.04	21.58	3.54	74.30	40.43
W2166	18.47	22.69	16.56	20.55	4.00	15.48	0.67
W2180	21.72	26.37	20.34	23.23	2.89	53.99	30.14
W2186	21.11	26.46	19.06	24.09	5.03	82.28	61.26
W2194	19.76	24.33	18.78	20.87	2.09	73.99	40.98
W2199	18.71	22.49	17.46	19.97	2.51	90.06	60.76
W2205	21.01	24.44	19.75	22.32	2.57	83.26	45.69
W2217	18.74	24.47	17.09	20.89	3.80	17.58	6.18
W2219	14.15	17.10	13.59	14.84	1.25	71.50	17.00
W2226	18.81	22.43	17.59	20.01	2.42	92.37	47.85
W2256	12.77	16.48	12.00	13.78	1.78	42.16	12.77
W2258	19.25	23.03	17.68	21.07	3.40	20.06	22.83
W2374	21.72	25.88	20.70	23.12	2.42	93.35	37.36
W2382	19.16	23.44	18.32	20.19	1.87	20.10	13.42
W2385	19.75	23.66	18.28	21.37	3.09	87.68	21.41
W2453	19.38	24.30	17.96	20.85	2.88	86.48	12.30

Appendix F.5. Reach-scale variables for each site within the water quality predictor category. Codes are referenced in Appendix F.1.

UniqueID	DO.min	DO.mean	DO.cv	Cond.max	Cond.mean	Cond.cv	Nitrate.max	Nitrate.mean	Nitrate.cv
B0052	5.34	8.88	0.34	1192.00	559.94	0.65	57.40	13.96	1.75
B0067	3.02	6.18	0.35	451.30	419.27	0.06	9.60	2.55	1.36
B0139	5.14	7.85	0.22	440.00	342.22	0.20	34.73	8.42	1.55
B0143	5.69	7.84	0.29	240.60	205.07	0.11	5.82	1.67	1.28
B0157	5.25	8.59	0.36	422.70	288.12	0.29	4.43	1.27	1.39
B0439	3.11	5.97	0.41	993.00	500.38	0.55	1.63	0.82	0.67
B0440	9.90	10.39	0.08	228.00	173.70	0.26	4.30	1.47	1.29
B0450	5.80	8.23	0.24	338.90	248.17	0.26	3.20	1.26	0.97
B0575	9.91	11.57	0.14	355.50	246.38	0.27	16.27	4.39	1.52
B0612	6.15	8.18	0.17	374.80	284.09	0.19	13.65	3.17	1.62
B0650	4.63	9.37	0.28	395.40	270.77	0.37	132.74	21.74	2.26
K0001	5.68	9.44	0.27	336.90	290.63	0.14	12.25	6.58	0.77
K0002	6.42	8.60	0.22	356.20	258.60	0.21	5.67	2.01	1.06
SID2171	8.44	9.27	0.10	253.60	223.14	0.19	2.49	1.29	0.72
SID2507	7.85	9.73	0.17	1067.00	974.50	0.09	3.69	2.15	0.69
SID2630	5.38	7.80	0.34	782.90	398.30	0.53	31.98	7.34	1.65
SID3026	7.24	9.66	0.22	206.80	178.22	0.12	15.32	3.72	1.75
SID3029	5.23	8.61	0.33	325.70	297.08	0.11	6.06	1.94	1.22
SID3054	5.47	9.82	0.25	573.00	470.39	0.14	12.66	3.57	1.43
SID4016	3.95	7.97	0.35	1139.00	540.50	0.45	2.69	1.17	0.72
SID4928	4.79	7.19	0.31	380.00	291.20	0.19	5.27	2.16	0.92
W0344	5.48	8.21	0.29	307.90	256.10	0.17	12.83	6.05	0.80
W2152	4.56	6.98	0.23	686.00	366.93	0.39	8.33	2.81	1.17
W2154	5.56	7.24	0.19	300.90	257.87	0.11	2.62	1.26	0.74
W2158	5.64	8.62	0.27	250.80	191.65	0.19	152.68	27.17	2.27
W2166	4.82	9.15	0.41	177.10	141.10	0.20	24.76	6.81	1.76
W2180	10.21	10.62	0.06	344.90	282.92	0.24	1.46	0.91	0.42
W2186	5.62	9.47	0.22	307.80	266.65	0.14	1.75	0.92	0.57
W2194	5.77	8.19	0.25	347.50	239.86	0.36	0.66	0.54	0.17
W2199	5.00	8.58	0.37	356.30	298.53	0.17	11.19	3.68	1.09
W2205	4.27	7.58	0.30	936.00	414.09	0.57	1.47	0.65	0.61
W2217	5.31	8.75	0.24	815.00	590.46	0.23	29.31	9.19	1.47
W2219	4.91	8.84	0.26	268.40	219.76	0.17	82.60	19.30	1.84
W2226	4.95	9.34	0.34	100.50	79.94	0.15	14.98	3.34	1.73
W2256	5.01	9.61	0.21	239.20	192.13	0.22	32.48	6.21	1.78
W2258	5.74	10.29	0.26	318.20	211.46	0.27	46.69	11.81	1.59
W2374	4.43	6.57	0.29	132.60	102.72	0.21	5.59	2.43	1.08
W2382	2.52	5.38	0.43	112.70	90.00	0.22	4.64	1.47	1.13
W2385	0.09	5.75	0.58	618.40	508.13	0.13	5.36	1.58	1.19
W2453	0.40	5.33	0.60	95.10	59.51	0.33	0.54	0.18	1.14

APPENDIX G:

PAIRWISE SPEARMAN RANK CORRELATION ANALYSIS FOR REACH-SCALE VARIABLES

Appendix G.1. Pairwise Spearman rank correlations for variables within the habitat predictor group.

	Bankfull area, mean	Bankfull area, cv	*Bankfull width, mean*	Bankfull width, cv	Pool habitat	*Riffle habitat*	Habitat unit transitions	Sediment, D16	*Sediment, D50*	*Sediment, D84*	Sediment, heterogeneity	*Sediment, gradation coefficient*	Sediment, sorting	Embeddedness	Banks, vegetated	Banks, eroded	Banks, undercut	Depositional features	Large wood, volume
Bankfull area, mean																			
Bankfull area, cv	-0.42																		
Bankfull width, mean	**0.86**	-0.22																	
Bankfull width, cv	-0.40	0.68	-0.15																
Pool habitat	0.08	0.28	0.17	0.03															
Riffle habitat	-0.18	0.44	0.07	0.27	0.16														
Habitat unit transitions	-0.04	0.41	0.10	0.28	0.54	0.34													
Sediment, D16	-0.07	0.27	0.16	0.11	0.19	**0.71**	0.41												
Sediment, D50	-0.01	0.34	0.22	0.12	0.22	**0.84**	0.39	**0.85**											
Sediment, D84	0.03	0.30	0.26	0.14	0.23	**0.80**	0.40	**0.79**	**0.97**										
Sediment, heterogeneity	0.00	-0.14	0.05	0.14	0.00	-0.08	0.16	-0.15	-0.14	-0.03									
Sediment, gradation coefficient	-0.07	0.16	0.14	0.28	0.09	0.48	0.24	0.13	0.47	0.57	0.51								
Sediment, sorting	-0.03	0.16	0.17	0.26	0.09	0.48	0.26	0.12	0.47	0.57	0.54	**0.98**							
Embeddedness	-0.05	0.05	0.12	0.16	-0.13	0.43	0.13	0.28	0.45	0.46	0.27	0.55	0.58						
Banks, vegetated	0.07	-0.16	0.02	-0.11	0.05	-0.27	-0.37	-0.22	-0.29	-0.33	0.00	-0.22	-0.21	-0.13					
Banks, eroded	0.01	-0.36	-0.10	-0.22	-0.16	-0.42	-0.25	-0.39	-0.46	-0.42	-0.20	-0.27	-0.30	-0.15	0.01				
Banks, undercut	-0.08	0.03	-0.09	0.01	0.11	0.02	0.09	0.11	0.12	0.12	-0.26	-0.03	-0.09	0.11	-0.20	0.35			
Depositional features	-0.03	0.06	0.21	0.01	0.40	0.15	0.18	0.14	0.01	0.02	-0.15	-0.07	-0.12	-0.19	0.02	0.23	0.11		
Large wood, volume	0.30	0.08	0.39	-0.13	0.43	0.27	0.36	0.39	0.35	0.31	-0.20	-0.06	-0.01	-0.07	-0.31	-0.05	0.26	0.30	

Note: Highly collinear variables (r ≥ |0.7|) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

Appendix G.2. Pairwise Spearman rank correlations for predictor variables within the flow predictor group.

	Slope	Width:depth ratio, mean	Width:depth ratio, cv	Entrenchment, mean	Entrenchment, cv	Stream power
Slope						
Width:depth ratio, mean	0.31					
Width:depth ratio, cv	0.19	0.40				
Entrenchment, mean	-0.47	-0.39	0.22			
Entrenchment, cv	0.12	0.16	0.39	0.05		
Stream power	**0.95**	0.27	0.09	-0.55	0.15	

Note: Highly collinear variables ($r \geq |0.7|$) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

Appendix G.3. Pairwise Spearman rank correlations for predictor variables within the temperature predictor group.

	Mean summer daily mean temp	*Max summer daily mean temp*	*Mean summer daily min temp*	Mean summer daily max temp	Mean summer daily temp range	Canopy cover	Riparian vegetation
Mean summer daily mean temp							
Max summer daily mean temp	**0.82**						
Mean summer daily min temp	**0.97**	**0.82**					
Mean summer daily max temp	**0.96**	**0.80**	**0.90**				
Mean summer daily temp range	0.05	0.02	-0.12	0.26			
Canopy cover	0.08	0.00	0.12	0.02	-0.14		
Riparian vegetation	0.19	0.19	0.27	0.13	-0.23	0.64	

Note: Highly collinear variables (r ≥ |0.7|) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

Appendix G.4. Pairwise Spearman rank correlations for predictor variables within the water quality predictor group.

	Dissolved oxygen, min	Dissolved oxygen, mean	Dissolved oxygen, cv	*Specific conductance, max*	Specific conductance, mean	Specific conductance, cv	*Nitrate, max*	Nitrate, mean	*Nitrate, cv*
Dissolved oxygen, min									
Dissolved oxygen, mean	0.68								
Dissolved oxygen, cv	**-0.78**	-0.59							
Specific conductance, max	-0.13	-0.14	0.09						
Specific conductance, mean	-0.15	-0.13	0.10	**0.95**					
Specific conductance, cv	-0.16	-0.11	0.13	0.31	0.08				
Nitrate, max	0.01	0.31	-0.01	-0.01	-0.04	-0.07			
Nitrate, mean	0.05	0.35	-0.05	0.02	0.00	-0.10	**0.97**		
Nitrate, cv	-0.08	0.24	0.08	-0.17	-0.23	0.00	**0.87**	**0.78**	

Note: Highly collinear variables (r ≥ |0.7|) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

APPENDIX H:

SINGLE-VARIABLE MODEL COMPARISON FOR REACH-SCALE PREDICTORS

Appendix H.1. Macroinvertebrate richness models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Sediment, D16	**273.517**	**274.660**	**0.000**	**0.306**		**Depositional features**	**137.551**	**140.218**	**0.000**	**0.209**		**Sediment, D16**	**133.515**	**136.181**	**0.000**	**0.490**
	Bankfull area, mean	274.585	275.728	1.068	0.180		Habitat unit transitions	138.409	141.075	0.858	0.136		Bankfull area, cv	133.770	136.437	0.256	0.431
	Bankfull area, cv	274.844	275.987	1.327	0.158		Bankfull area, mean	139.008	141.675	1.457	0.101		Depositional features	140.019	142.686	6.505	0.019
	Bankfull width, cv	276.321	277.464	2.804	0.075		Banks, vegetated	139.012	141.679	1.461	0.101		Large wood, volume	140.783	143.449	7.268	0.013
	Sediment, heterogeneity	278.029	279.172	4.512	0.032		Sediment, D16	140.011	142.677	2.460	0.061		Bankfull area, mean	141.212	143.879	7.697	0.010
	Banks, undercut	278.036	279.179	4.519	0.032		Pool habitat	140.111	142.778	2.560	0.058		Bankfull width, cv	142.093	144.760	8.578	0.007
	Pool habitat	278.151	279.294	4.634	0.030		Embeddedness	140.341	143.008	2.790	0.052		Habitat unit transitions	142.397	145.064	8.882	0.006
	Banks, vegetated	278.152	279.295	4.635	0.030		Sediment, sorting (stnd dev)	140.404	143.071	2.853	0.050		Banks, undercut	143.204	145.871	9.689	0.004
	Habitat unit transitions	278.369	279.512	4.852	0.027		Bankfull width, cv	140.688	143.355	3.137	0.044		Banks, eroded	143.228	145.895	9.714	0.004
	Embeddedness	278.427	279.570	4.910	0.026		Sediment, heterogeneity	140.768	143.435	3.217	0.042		Banks, vegetated	143.478	146.145	9.963	0.003
	Depositional features	278.437	279.580	4.920	0.026		Banks, eroded	140.935	143.602	3.384	0.039		Embeddedness	143.533	146.200	10.019	0.003
	Sediment, sorting (stnd dev)	278.465	279.608	4.948	0.026		Bankfull area, cv	141.028	143.695	3.477	0.037		Pool habitat	143.568	146.235	10.054	0.003
	Large wood, volume	278.473	279.616	4.956	0.026		Banks, undercut	141.076	143.742	3.525	0.036		Sediment, sorting (stnd dev)	143.640	146.307	10.125	0.003
	Banks, eroded	278.476	279.619	4.959	0.026		Large wood, volume	141.127	143.794	3.576	0.035		Sediment, heterogeneity	143.651	146.317	10.136	0.003
Flow						Flow						Flow					
	Entrenchment, mean	**277.156**	**278.299**	**0.000**	**0.289**		**Entrenchment, mean**	**138.751**	**141.417**	**0.000**	**0.418**		**Stream power**	**141.317**	**143.984**	**0.000**	**0.437**
	Stream power	277.477	278.620	0.321	0.246		Width:depth ratio, mean	140.585	143.252	1.834	0.167		Entrenchment, mean	143.452	146.119	2.135	0.150
	Width:depth ratio, mean	278.334	279.477	1.177	0.160		Width:depth ratio, cv	140.757	143.423	2.006	0.153		Width:depth ratio, cv	143.583	146.250	2.266	0.141
	Width:depth ratio, cv	278.441	279.584	1.285	0.152		Stream power	141.019	143.686	2.268	0.134		Width:depth ratio, mean	143.652	146.319	2.335	0.136
	Entrenchment, cv	278.443	279.586	1.287	0.152		Entrenchment, cv	141.113	143.780	2.362	0.128		Entrenchment, cv	143.654	146.321	2.337	0.136
Temperature						Temperature						Temperature					
	Mean summer daily max temp	**275.729**	**276.872**	**0.000**	**0.462**		**Canopy cover**	**137.213**	**139.879**	**0.000**	**0.663**		**Mean summer daily max temp**	**137.972**	**140.639**	**0.000**	**0.614**
	Mean summer daily temp range	277.292	278.435	1.563	0.211		Mean summer daily temp range	140.449	143.116	3.236	0.132		Mean summer daily temp range	139.489	142.155	1.517	0.288
	Canopy cover	277.669	278.812	1.940	0.175		Riparian vegetation	140.867	143.534	3.655	0.107		Riparian vegetation	142.586	145.253	4.614	0.061
	Riparian vegetation	277.958	279.101	2.230	0.152		Mean summer daily max temp	141.032	143.699	3.819	0.098		Canopy cover	143.565	146.232	5.593	0.037
Water quality						Water quality						Water quality					
	Nitrate, mean	**272.443**	**273.586**	**0.000**	**0.773**		**Nitrate, mean**	**135.275**	**137.942**	**0.000**	**0.684**		**Specific conductance, mean**	**141.599**	**144.265**	**0.000**	**0.376**
	Dissolved oxygen, mean	276.530	277.673	4.088	0.100		Dissolved oxygen, mean	138.511	141.178	3.236	0.136		Nitrate, mean	142.897	145.564	1.298	0.196
	Specific conductance, mean	277.873	279.016	5.430	0.051		Specific conductance, mean	139.517	142.184	4.242	0.082		Specific conductance, cv	143.453	146.120	1.855	0.149
	Dissolved oxygen, cv	278.443	279.586	6.000	0.038		Specific conductance, cv	140.120	142.787	4.845	0.061		Dissolved oxygen, mean	143.530	146.196	1.931	0.143
	Specific conductance, cv	278.478	279.621	6.036	0.038		Dissolved oxygen, cv	141.109	143.775	5.833	0.037		Dissolved oxygen, cv	143.628	146.295	2.029	0.136

Appendix H.2. Fish richness models with impervious cover and one additional predictor. Model selection was performed with Akaike’s Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Depositional features	**178.079**	**178.746**	**0.000**	**0.129**		**Banks, vegetated**	**87.386**	**88.886**	**0.000**	**0.383**		**Depositional features**	**86.857**	**88.357**	**0.000**	**0.309**
	Bankfull area, mean	178.081	178.748	0.002	0.128		Embeddedness	90.247	91.747	2.861	0.092		Habitat unit transitions	89.590	91.090	2.733	0.079
	Banks, vegetated	178.652	179.319	0.573	0.097		Sediment, sorting (stnd dev)	90.374	91.874	2.988	0.086		Bankfull area, mean	89.844	91.344	2.987	0.069
	Banks, undercut	179.059	179.726	0.979	0.079		Banks, eroded	90.760	92.260	3.374	0.071		Pool habitat	89.898	91.398	3.041	0.068
	Embeddedness	179.203	179.870	1.124	0.073		Bankfull area, mean	91.053	92.553	3.666	0.061		Sediment, sorting (stnd dev)	90.022	91.522	3.165	0.063
	Large wood, volume	179.305	179.971	1.225	0.070		Banks, undercut	91.677	93.177	4.291	0.045		Large wood, volume	90.373	91.873	3.516	0.053
	Sediment, heterogeneity	179.667	180.334	1.588	0.058		Large wood, volume	91.723	93.223	4.337	0.044		Sediment, heterogeneity	90.399	91.899	3.542	0.053
	Bankfull area, cv	179.716	180.383	1.637	0.057		Sediment, D16	92.020	93.520	4.634	0.038		Banks, vegetated	90.537	92.037	3.680	0.049
	Banks, eroded	179.721	180.387	1.641	0.057		Bankfull area, cv	92.252	93.752	4.866	0.034		Banks, eroded	90.588	92.088	3.731	0.048
	Pool habitat	179.835	180.502	1.756	0.053		Habitat unit transitions	92.383	93.883	4.997	0.031		Embeddedness	90.702	92.202	3.845	0.045
	Habitat unit transitions	179.933	180.599	1.853	0.051		Sediment, heterogeneity	92.461	93.961	5.074	0.030		Sediment, D16	90.873	92.373	4.016	0.041
	Sediment, D16	179.934	180.601	1.855	0.051		Depositional features	92.529	94.029	5.142	0.029		Bankfull width, cv	90.880	92.380	4.023	0.041
	Sediment, sorting (stnd dev)	179.980	180.647	1.901	0.050		Bankfull width, cv	92.586	94.086	5.200	0.028		Banks, undercut	90.896	92.396	4.039	0.041
	Bankfull width, cv	180.048	180.715	1.969	0.048		Pool habitat	92.594	94.094	5.207	0.028		Bankfull area, cv	90.909	92.409	4.052	0.041
Flow						Flow						Flow					
	Entrenchment, cv	**174.685**	**175.351**	**0.000**	**0.639**		**Width:depth ratio, mean**	**91.369**	**92.869**	**0.000**	**0.279**		**Entrenchment, cv**	**84.604**	**86.104**	**0.000**	**0.812**
	Width:depth ratio, cv	177.666	178.333	2.981	0.144		Width:depth ratio, cv	91.515	93.015	0.147	0.259		Width:depth ratio, cv	89.979	91.479	5.375	0.055
	Width:depth ratio, mean	177.908	178.575	3.224	0.128		Stream power	92.488	93.988	1.120	0.159		Entrenchment, mean	90.331	91.831	5.727	0.046
	Entrenchment, mean	179.980	180.647	5.296	0.045		Entrenchment, cv	92.596	94.096	1.228	0.151		Width:depth ratio, mean	90.349	91.849	5.744	0.046
	Stream power	180.046	180.713	5.361	0.044		Entrenchment, mean	92.597	94.097	1.229	0.151		Stream power	90.606	92.106	6.002	0.040
Temperature						Temperature						Temperature					
	Mean summer daily temp range	**179.744**	**180.410**	**0.000**	**0.262**		**Mean summer daily temp range**	**91.057**	**92.557**	**0.000**	**0.362**		**Mean summer daily temp range**	**90.829**	**92.329**	**0.000**	**0.256**
	Canopy cover	179.773	180.440	0.030	0.258		Canopy cover	91.624	93.124	0.567	0.272		Canopy cover	90.855	92.355	0.026	0.253
	Riparian vegetation	179.910	180.577	0.166	0.241		Mean summer daily max temp	92.256	93.756	1.199	0.199		Mean summer daily max temp	90.909	92.409	0.080	0.246
	Mean summer daily max temp	179.927	180.594	0.183	0.239		Riparian vegetation	92.596	94.096	1.539	0.168		Riparian vegetation	90.919	92.419	0.090	0.245
Water quality						Water quality						Water quality					
	Dissolved oxygen, mean	**175.754**	**176.421**	**0.000**	**0.539**		**Dissolved oxygen, mean**	**89.217**	**90.717**	**0.000**	**0.515**		**Specific conductance, mean**	**87.229**	**88.729**	**0.000**	**0.534**
	Dissolved oxygen, cv	177.692	178.358	1.938	0.204		Dissolved oxygen, cv	91.570	93.070	2.353	0.159		Dissolved oxygen, cv	89.731	91.231	2.502	0.153
	Specific conductance, mean	178.689	179.356	2.935	0.124		Specific conductance, mean	91.998	93.498	2.781	0.128		Dissolved oxygen, mean	90.093	91.593	2.864	0.128
	Specific conductance, cv	179.937	180.604	4.183	0.067		Specific conductance, cv	92.476	93.976	3.259	0.101		Nitrate, mean	90.564	92.064	3.334	0.101
	Nitrate, mean	179.941	180.607	4.187	0.066		Nitrate, mean	92.566	94.066	3.349	0.097		Specific conductance, cv	90.917	92.417	3.688	0.084

Appendix H.3. Macroinvertebrate flow traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Bankfull area, cv	**192.931**	**194.073**	**0.000**	**0.422**		**Depositional features**	**85.460**	**88.127**	**0.000**	**0.538**		**Bankfull area, cv**	**91.332**	**93.998**	**0.000**	**0.958**
	Bankfull width, cv	194.751	195.894	1.820	0.170		Sediment, heterogeneity	89.080	91.747	3.620	0.088		Sediment, D16	98.837	101.504	7.505	0.022
	Sediment, D16	195.908	197.051	2.978	0.095		Bankfull area, cv	90.039	92.705	4.578	0.054		Bankfull width, cv	100.408	103.075	9.077	0.010
	Banks, eroded	197.150	198.292	4.219	0.051		Banks, eroded	90.461	93.128	5.001	0.044		Sediment, heterogeneity	102.868	105.535	11.536	0.003
	Depositional features	198.051	199.194	5.121	0.033		Habitat unit transitions	91.125	93.792	5.665	0.032		Large wood, volume	104.098	106.764	12.766	0.002
	Bankfull width, mean	198.117	199.260	5.186	0.032		Banks, undercut	91.159	93.826	5.699	0.031		Bankfull width, mean	105.726	108.393	14.395	0.001
	Sediment, heterogeneity	198.215	199.358	5.284	0.030		Banks, vegetated	91.287	93.954	5.827	0.029		Banks, eroded	106.155	108.822	14.824	0.001
	Banks, vegetated	198.455	199.597	5.524	0.027		Bankfull area, mean	91.327	93.993	5.866	0.029		Embeddedness	106.191	108.857	14.859	0.001
	Embeddedness	198.533	199.676	5.602	0.026		Pool habitat	91.450	94.117	5.990	0.027		Sediment, sorting (stnd dev)	106.476	109.142	15.144	0.000
	Sediment, sorting (stnd dev)	198.691	199.834	5.761	0.024		Embeddedness	91.458	94.125	5.998	0.027		Habitat unit transitions	106.541	109.208	15.209	0.000
	Pool habitat	198.698	199.840	5.767	0.024		Bankfull width, cv	91.515	94.181	6.055	0.026		Banks, vegetated	106.672	109.339	15.341	0.000
	Large wood, volume	198.759	199.902	5.828	0.023		Sediment, D16	91.553	94.219	6.092	0.026		Banks, undercut	106.689	109.355	15.357	0.000
	Habitat unit transitions	198.769	199.912	5.839	0.023		Sediment, sorting (stnd dev)	91.582	94.249	6.122	0.025		Pool habitat	106.809	109.475	15.477	0.000
	Banks, undercut	198.775	199.918	5.845	0.023		Large wood, volume	91.634	94.301	6.174	0.025		Depositional features	106.817	109.484	15.485	0.000
Flow						Flow						Flow					
	Entrenchment, mean	**196.921**	**198.063**	**0.000**	**0.292**		**Entrenchment, mean**	**89.246**	**91.913**	**0.000**	**0.346**		Stream power	**103.649**	**106.316**	**0.000**	**0.366**
	Width:depth ratio, mean	197.163	198.306	0.243	0.259		Width:depth ratio, mean	89.894	92.560	0.648	0.250		Width:depth ratio, cv	104.038	106.705	0.389	0.301
	Width:depth ratio, cv	198.046	199.189	1.125	0.166		Width:depth ratio, cv	90.392	93.059	1.146	0.195		Entrenchment, mean	105.761	108.428	2.112	0.127
	Stream power	198.116	199.259	1.195	0.161		Entrenchment, cv	91.490	94.156	2.244	0.113		Width:depth ratio, mean	105.931	108.598	2.282	0.117
	Entrenchment, cv	198.663	199.806	1.742	0.122		Stream power	91.783	94.450	2.537	0.097		Entrenchment, cv	106.488	109.155	2.839	0.088
Temperature						Temperature						Temperature					
	Mean summer daily max temp	**192.169**	**193.312**	**0.000**	**0.603**		**Mean summer daily max temp**	**90.600**	**93.267**	**0.000**	**0.328**		Mean summer daily max temp	**98.846**	**101.512**	**0.000**	**0.620**
	Mean summer daily temp range	193.248	194.391	1.080	0.351		Canopy cover	90.662	93.329	0.061	0.318		Mean summer daily temp range	99.994	102.661	1.148	0.349
	Canopy cover	198.714	199.857	6.545	0.023		Riparian vegetation	91.826	94.493	1.226	0.178		Canopy cover	106.072	108.738	7.226	0.017
	Riparian vegetation	198.726	199.868	6.557	0.023		Mean summer daily temp range	91.838	94.505	1.238	0.177		Riparian vegetation	106.476	109.143	7.631	0.014
Water quality						Water quality						Water quality					
	Nitrate, mean	**194.395**	**195.538**	**0.000**	**0.421**		**Nitrate, mean**	**86.147**	**88.813**	**0.000**	**0.709**		Dissolved oxygen, cv	**103.212**	**105.878**	**0.000**	**0.381**
	Dissolved oxygen, cv	194.492	195.635	0.097	0.401		Dissolved oxygen, mean	89.822	92.488	3.675	0.113		Dissolved oxygen, mean	103.450	106.117	0.238	0.338
	Dissolved oxygen, mean	198.165	199.308	3.770	0.064		Specific conductance, mean	90.921	93.588	4.774	0.065		Specific conductance, cv	105.742	108.409	2.531	0.107
	Specific conductance, cv	198.306	199.449	3.911	0.060		Specific conductance, cv	91.130	93.797	4.984	0.059		Nitrate, mean	105.844	108.510	2.632	0.102
	Specific conductance, mean	198.501	199.643	4.106	0.054		Dissolved oxygen, cv	91.271	93.937	5.124	0.055		Specific conductance, mean	106.557	109.223	3.345	0.072

Appendix H.4. Fish flow traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Habitat unit transitions	**174.644**	**175.787**	**0.000**	**0.170**		**Sediment, D16**	**94.349**	**97.016**	**0.000**	**0.152**		**Banks, vegetated**	**79.489**	**82.155**	**0.000**	**0.146**
	Banks, vegetated	175.142	176.285	0.498	0.133		Habitat unit transitions	94.608	97.274	0.259	0.134		Sediment, heterogeneity	79.812	82.479	0.323	0.124
	Sediment, D16	175.289	176.432	0.645	0.123		Large wood, volume	94.908	97.574	0.559	0.115		Depositional features	80.069	82.736	0.581	0.109
	Sediment, heterogeneity	176.108	177.251	1.464	0.082		Sediment, heterogeneity	95.679	98.345	1.330	0.078		Habitat unit transitions	80.641	83.307	1.152	0.082
	Large wood, volume	176.369	177.512	1.725	0.072		Depositional features	95.898	98.565	1.550	0.070		Bankfull width, cv	80.972	83.639	1.483	0.069
	Embeddedness	176.871	178.014	2.227	0.056		Sediment, sorting (stnd dev)	96.071	98.738	1.722	0.064		Large wood, volume	81.284	83.950	1.795	0.059
	Pool habitat	177.051	178.194	2.407	0.051		Bankfull area, mean	96.384	99.050	2.035	0.055		Pool habitat	81.350	84.017	1.861	0.057
	Sediment, sorting (stnd dev)	177.135	178.278	2.491	0.049		Bankfull area, cv	96.426	99.093	2.077	0.054		Sediment, D16	81.357	84.024	1.868	0.057
	Bankfull width, cv	177.144	178.287	2.500	0.049		Banks, vegetated	96.471	99.138	2.122	0.053		Embeddedness	81.531	84.197	2.042	0.052
	Depositional features	177.322	178.465	2.678	0.045		Embeddedness	96.582	99.248	2.233	0.050		Bankfull area, mean	81.615	84.281	2.126	0.050
	Bankfull area, mean	177.338	178.481	2.694	0.044		Banks, eroded	96.705	99.372	2.356	0.047		Banks, eroded	81.617	84.284	2.129	0.050
	Banks, undercut	177.423	178.566	2.779	0.042		Banks, undercut	96.712	99.379	2.363	0.047		Bankfull area, cv	81.684	84.351	2.196	0.049
	Bankfull area, cv	177.423	178.566	2.779	0.042		Pool habitat	96.919	99.586	2.570	0.042		Banks, undercut	81.714	84.381	2.226	0.048
	Banks, eroded	177.481	178.624	2.837	0.041		Bankfull width, cv	97.008	99.675	2.660	0.040		Sediment, sorting (stnd dev)	81.734	84.401	2.246	0.047
Flow						Flow						Flow					
	Stream power	**172.245**	**173.388**	**0.000**	**0.477**		**Stream power**	**93.626**	**96.292**	**0.000**	**0.522**		**Width:depth ratio, cv**	**73.184**	**75.850**	**0.000**	**0.733**
	Width:depth ratio, cv	173.756	174.899	1.511	0.224		Entrenchment, cv	96.154	98.821	2.528	0.147		Entrenchment, mean	76.436	79.103	3.253	0.144
	Entrenchment, mean	173.924	175.067	1.679	0.206		Width:depth ratio, cv	96.511	99.177	2.885	0.123		Stream power	78.090	80.757	4.906	0.063
	Width:depth ratio, mean	176.488	177.630	4.243	0.057		Width:depth ratio, mean	96.811	99.478	3.185	0.106		Width:depth ratio, mean	78.750	81.417	5.566	0.045
	Entrenchment, cv	177.401	178.543	5.156	0.036		Entrenchment, mean	96.897	99.563	3.271	0.102		Entrenchment, cv	81.092	83.759	7.909	0.014
Temperature						Temperature						Temperature					
	Riparian vegetation	**174.633**	**175.776**	**0.000**	**0.551**		**Riparian vegetation**	**95.791**	**98.458**	**0.000**	**0.359**		**Riparian vegetation**	**79.454**	**82.120**	**0.000**	**0.473**
	Canopy cover	176.859	178.002	2.226	0.181		Canopy cover	96.615	99.282	0.824	0.238		Canopy cover	81.372	84.038	1.918	0.181
	Mean summer daily max temp	177.464	178.607	2.831	0.134		Mean summer daily temp range	96.899	99.565	1.108	0.206		Mean summer daily max temp	81.384	84.050	1.930	0.180
	Mean summer daily temp range	177.466	178.609	2.833	0.134		Mean summer daily max temp	96.991	99.657	1.200	0.197		Mean summer daily temp range	81.544	84.211	2.091	0.166
Water quality						Water quality						Water quality					
	Dissolved oxygen, mean	**166.823**	**167.966**	**0.000**	**0.951**		**Specific conductance, mean**	**93.533**	**96.199**	**0.000**	**0.499**		**Dissolved oxygen, mean**	**70.896**	**73.563**	**0.000**	**0.859**
	Dissolved oxygen, cv	173.723	174.866	6.901	0.030		Nitrate, mean	95.735	98.401	2.202	0.166		Specific conductance, mean	75.260	77.926	4.363	0.097
	Specific conductance, mean	176.325	177.467	9.502	0.008		Dissolved oxygen, mean	96.004	98.670	2.471	0.145		Dissolved oxygen, cv	77.373	80.040	6.477	0.034
	Nitrate, mean	177.197	178.340	10.375	0.005		Specific conductance, cv	96.792	99.459	3.260	0.098		Specific conductance, cv	80.991	83.657	10.094	0.006
	Specific conductance, cv	177.241	178.384	10.418	0.005		Dissolved oxygen, cv	96.921	99.587	3.388	0.092		Nitrate, mean	81.503	84.169	10.606	0.004

Appendix H.5. Macroinvertebrate thermal traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Sediment, D16	**173.386**	**174.529**	**0.000**	**0.304**		**Bankfull width, cv**	**87.579**	**90.246**	**0.000**	**0.209**		**Large wood, volume**	**83.562**	**86.228**	**0.000**	**0.701**
	Banks, vegetated	174.764	175.907	1.378	0.152		Sediment, D16	88.668	91.334	1.088	0.121		Sediment, D16	86.747	89.414	3.186	0.142
	Pool habitat	174.790	175.933	1.404	0.150		Banks, vegetated	89.224	91.890	1.644	0.092		Pool habitat	89.356	92.023	5.794	0.039
	Habitat unit transitions	176.119	177.262	2.733	0.077		Habitat unit transitions	89.545	92.212	1.966	0.078		Bankfull area, cv	91.030	93.697	7.468	0.017
	Bankfull area, cv	177.096	178.239	3.710	0.048		Pool habitat	89.861	92.527	2.281	0.067		Banks, undercut	91.230	93.897	7.669	0.015
	Banks, undercut	177.106	178.249	3.720	0.047		Sediment, heterogeneity	89.866	92.532	2.286	0.067		Bankfull area, mean	91.615	94.282	8.054	0.012
	Bankfull area, mean	177.582	178.725	4.196	0.037		Embeddedness	90.166	92.832	2.586	0.057		Habitat unit transitions	91.665	94.331	8.103	0.012
	Embeddedness	177.887	179.030	4.501	0.032		Sediment, sorting (stnd dev)	90.291	92.958	2.712	0.054		Banks, vegetated	91.693	94.359	8.131	0.012
	Bankfull width, cv	177.943	179.086	4.557	0.031		Bankfull area, mean	90.313	92.980	2.734	0.053		Sediment, heterogeneity	91.816	94.483	8.255	0.011
	Depositional features	178.204	179.347	4.818	0.027		Banks, undercut	90.462	93.128	2.882	0.049		Depositional features	91.822	94.488	8.260	0.011
	Large wood, volume	178.387	179.530	5.001	0.025		Large wood, volume	90.904	93.570	3.325	0.040		Embeddedness	92.581	95.248	9.020	0.008
	Sediment, heterogeneity	178.458	179.601	5.072	0.024		Banks, eroded	90.979	93.646	3.400	0.038		Sediment, sorting (stnd dev)	92.760	95.426	9.198	0.007
	Banks, eroded	178.568	179.711	5.182	0.023		Depositional features	90.988	93.654	3.409	0.038		Banks, eroded	93.004	95.671	9.443	0.006
	Sediment, sorting (stnd dev)	178.653	179.795	5.267	0.022		Bankfull area, cv	91.059	93.726	3.480	0.037		Bankfull width, cv	93.039	95.705	9.477	0.006
Flow						Flow						Flow					
	Width:depth ratio, mean	**174.024**	**175.167**	**0.000**	**0.563**		**Stream power**	**87.661**	**90.328**	**0.000**	**0.497**		**Width:depth ratio, mean**	**83.660**	**86.327**	**0.000**	**0.895**
	Stream power	176.235	177.378	2.211	0.187		Width:depth ratio, cv	89.372	92.039	1.711	0.211		Width:depth ratio, cv	88.681	91.347	5.021	0.073
	Entrenchment, mean	177.590	178.733	3.566	0.095		Entrenchment, mean	90.855	93.521	3.194	0.101		Entrenchment, mean	91.845	94.512	8.185	0.015
	Width:depth ratio, cv	177.699	178.842	3.675	0.090		Entrenchment, cv	90.871	93.538	3.210	0.100		Entrenchment, cv	92.900	95.566	9.240	0.009
	Entrenchment, cv	178.324	179.467	4.300	0.066		Width:depth ratio, mean	91.052	93.719	3.391	0.091		Stream power	92.984	95.651	9.324	0.008
Temperature						Temperature						Temperature					
	Riparian vegetation	**175.071**	**176.214**	**0.000**	**0.507**		**Mean summer daily max temp**	**89.515**	**92.181**	**0.000**	**0.340**		**Riparian vegetation**	**90.238**	**92.905**	**0.000**	**0.527**
	Mean summer daily max temp	176.706	177.849	1.635	0.224		Riparian vegetation	89.889	92.556	0.375	0.282		Mean summer daily max temp	92.463	95.129	2.224	0.173
	Mean summer daily temp range	177.449	178.592	2.378	0.155		Mean summer daily temp range	90.456	93.123	0.942	0.213		Mean summer daily temp range	92.684	95.351	2.446	0.155
	Canopy cover	178.057	179.199	2.986	0.114		Canopy cover	90.969	93.636	1.454	0.165		Canopy cover	92.818	95.485	2.580	0.145
Water quality						Water quality						Water quality					
	Specific conductance, mean	**175.453**	**176.596**	**0.000**	**0.358**		**Specific conductance, cv**	**88.823**	**91.490**	**0.000**	**0.330**		**Specific conductance, mean**	**85.905**	**88.571**	**0.000**	**0.810**
	Nitrate, mean	175.946	177.089	0.493	0.280		Dissolved oxygen, cv	89.652	92.318	0.829	0.218		Nitrate, mean	89.885	92.551	3.980	0.111
	Dissolved oxygen, mean	177.193	178.336	1.740	0.150		Dissolved oxygen, mean	90.048	92.715	1.225	0.179		Dissolved oxygen, mean	92.478	95.145	6.574	0.030
	Dissolved oxygen, cv	177.803	178.946	2.350	0.111		Nitrate, mean	90.364	93.031	1.541	0.153		Dissolved oxygen, cv	92.706	95.373	6.802	0.027
	Specific conductance, cv	177.962	179.105	2.509	0.102		Specific conductance, mean	90.845	93.512	2.022	0.120		Specific conductance, cv	93.152	95.818	7.247	0.022

Appendix H.6. Fish thermal traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Large wood, volume	**152.890**	**154.033**	**0.000**	**0.487**		**Large wood, volume**	**97.402**	**100.069**	**0.000**	**0.736**		**Sediment, heterogeneity**	**54.919**	**57.585**	**0.000**	**0.324**
	Sediment, D16	155.898	157.040	3.007	0.108		Banks, undercut	102.719	105.386	5.318	0.052		Depositional features	56.595	59.262	1.676	0.140
	Sediment, heterogeneity	156.232	157.375	3.342	0.092		Sediment, heterogeneity	103.559	106.226	6.157	0.034		Sediment, D16	56.938	59.604	2.019	0.118
	Banks, undercut	156.644	157.787	3.754	0.075		Sediment, D16	103.833	106.500	6.432	0.030		Large wood, volume	57.062	59.728	2.143	0.111
	Banks, vegetated	156.973	158.116	4.083	0.063		Banks, vegetated	104.037	106.704	6.635	0.027		Sediment, sorting (stnd dev)	58.221	60.887	3.302	0.062
	Bankfull width, cv	158.248	159.391	5.358	0.033		Embeddedness	104.450	107.116	7.048	0.022		Bankfull width, cv	59.615	62.282	4.696	0.031
	Depositional features	158.536	159.679	5.645	0.029		Bankfull width, cv	105.072	107.738	7.670	0.016		Banks, vegetated	59.627	62.293	4.708	0.031
	Sediment, sorting (stnd dev)	159.474	160.617	6.584	0.018		Bankfull area, cv	105.096	107.763	7.694	0.016		Banks, undercut	59.680	62.347	4.761	0.030
	Pool habitat	159.506	160.649	6.615	0.018		Pool habitat	105.586	108.252	8.184	0.012		Pool habitat	59.702	62.368	4.783	0.030
	Embeddedness	159.608	160.750	6.717	0.017		Habitat unit transitions	105.649	108.316	8.247	0.012		Embeddedness	59.824	62.491	4.906	0.028
	Bankfull area, cv	159.657	160.800	6.766	0.017		Bankfull area, mean	105.731	108.398	8.330	0.011		Bankfull area, cv	60.119	62.785	5.200	0.024
	Banks, eroded	159.756	160.899	6.866	0.016		Banks, eroded	105.740	108.407	8.339	0.011		Banks, eroded	60.162	62.829	5.243	0.024
	Habitat unit transitions	159.970	161.113	7.079	0.014		Sediment, sorting (stnd dev)	105.751	108.417	8.349	0.011		Bankfull area, mean	60.179	62.846	5.260	0.023
	Bankfull area, mean	160.040	161.183	7.150	0.014		Depositional features	105.755	108.421	8.353	0.011		Habitat unit transitions	60.182	62.848	5.263	0.023
Flow						Flow						Flow					
	Entrenchment, mean	**157.332**	**158.475**	**0.000**	**0.304**		**Entrenchment, mean**	**103.856**	**106.523**	**0.000**	**0.337**		**Stream power**	**53.351**	**56.018**	**0.000**	**0.752**
	Entrenchment, cv	158.007	159.150	0.674	0.217		Width:depth ratio, cv	104.946	107.613	1.090	0.196		Entrenchment, cv	56.953	59.620	3.602	0.124
	Stream power	158.013	159.156	0.680	0.217		Width:depth ratio, mean	105.121	107.788	1.265	0.179		Width:depth ratio, mean	59.004	61.671	5.653	0.045
	Width:depth ratio, mean	158.344	159.486	1.011	0.184		Stream power	105.356	108.022	1.500	0.159		Entrenchment, mean	59.088	61.754	5.737	0.043
	Width:depth ratio, cv	160.041	161.184	2.709	0.079		Entrenchment, cv	105.782	108.449	1.926	0.129		Width:depth ratio, cv	59.421	62.087	6.070	0.036
Temperature						Temperature						Temperature					
	Riparian vegetation	**155.717**	**156.860**	**0.000**	**0.446**		**Mean summer daily temp range**	**103.115**	**105.781**	**0.000**	**0.306**		**Riparian vegetation**	**58.296**	**60.963**	**0.000**	**0.376**
	Canopy cover	156.387	157.530	0.669	0.319		Mean summer daily max temp	103.304	105.971	0.190	0.278		Canopy cover	58.960	61.627	0.664	0.270
	Mean summer daily max temp	157.594	158.737	1.877	0.175		Riparian vegetation	103.774	106.441	0.659	0.220		Mean summer daily max temp	59.739	62.406	1.443	0.183
	Mean summer daily temp range	159.733	160.876	4.015	0.060		Canopy cover	103.999	106.666	0.885	0.196		Mean summer daily temp range	59.872	62.538	1.576	0.171
Water quality						Water quality						Water quality					
	Dissolved oxygen, mean	**156.682**	**157.825**	**0.000**	**0.489**		**Nitrate, mean**	**103.972**	**106.638**	**0.000**	**0.281**		**Dissolved oxygen, mean**	**56.725**	**59.392**	**0.000**	**0.500**
	Nitrate, mean	158.769	159.912	2.087	0.172		Specific conductance, cv	104.223	106.890	0.252	0.248		Specific conductance, mean	59.190	61.856	2.465	0.146
	Dissolved oxygen, cv	158.961	160.104	2.280	0.156		Specific conductance, mean	104.780	107.447	0.809	0.188		Specific conductance, cv	59.288	61.954	2.563	0.139
	Specific conductance, cv	160.038	161.181	3.356	0.091		Dissolved oxygen, mean	105.119	107.785	1.147	0.159		Dissolved oxygen, cv	59.536	62.202	2.811	0.123
	Specific conductance, mean	160.041	161.183	3.359	0.091		Dissolved oxygen, cv	105.609	108.276	1.638	0.124		Nitrate, mean	60.078	62.745	3.353	0.093

Appendix H.7. Macroinvertebrate tolerance index models with impervious cover and one additional predictor. Model selection was performed with Akaike’s Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Embeddedness	**99.630**	**100.773**	**0.000**	**0.814**		**Embeddedness**	**47.550**	**50.216**	**0.000**	**0.777**		**Embeddedness**	**47.672**	**50.339**	**0.000**	**0.610**
	Sediment, sorting (stnd dev)	102.822	103.965	3.192	0.165		Sediment, sorting (stnd dev)	50.485	53.152	2.935	0.179		Sediment, sorting (stnd dev)	50.057	52.723	2.384	0.185
	Banks, undercut	110.212	111.355	10.582	0.004		Banks, undercut	55.757	58.424	8.208	0.013		Banks, vegetated	50.411	53.077	2.738	0.155
	Large wood, volume	110.533	111.676	10.903	0.003		Large wood, volume	56.971	59.638	9.421	0.007		Habitat unit transitions	55.381	58.048	7.709	0.013
	Banks, eroded	111.427	112.570	11.797	0.002		Banks, eroded	57.504	60.170	9.954	0.005		Pool habitat	56.393	59.060	8.721	0.008
	Habitat unit transitions	111.750	112.893	12.120	0.002		Sediment, heterogeneity	58.871	61.537	11.321	0.003		Banks, undercut	57.473	60.140	9.801	0.005
	Banks, vegetated	111.858	113.001	12.228	0.002		Depositional features	59.033	61.699	11.483	0.002		Bankfull area, mean	57.668	60.335	9.996	0.004
	Sediment, heterogeneity	111.959	113.102	12.329	0.002		Pool habitat	59.487	62.154	11.937	0.002		Bankfull width, cv	57.718	60.384	10.045	0.004
	Pool habitat	112.495	113.638	12.865	0.001		Bankfull area, cv	59.507	62.174	11.958	0.002		Sediment, heterogeneity	58.038	60.704	10.366	0.003
	Bankfull width, cv	112.908	114.051	13.278	0.001		Bankfull area, mean	59.515	62.181	11.965	0.002		Depositional features	58.343	61.009	10.670	0.003
	Depositional features	113.166	114.309	13.536	0.001		Bankfull width, cv	59.533	62.199	11.983	0.002		Banks, eroded	58.501	61.167	10.829	0.003
	Sediment, D16	113.509	114.652	13.879	0.001		Habitat unit transitions	59.540	62.207	11.991	0.002		Bankfull area, cv	58.620	61.287	10.948	0.003
	Bankfull area, cv	113.641	114.784	14.011	0.001		Sediment, D16	59.544	62.211	11.994	0.002		Large wood, volume	58.667	61.334	10.995	0.002
	Bankfull area, mean	113.646	114.789	14.016	0.001		Banks, vegetated	59.581	62.247	12.031	0.002		Sediment, D16	58.701	61.368	11.029	0.002
Flow						Flow						Flow					
	Entrenchment, mean	**109.338**	**110.481**	**0.000**	**0.519**		**Width:depth ratio, mean**	**58.405**	**61.071**	**0.000**	**0.291**		**Entrenchment, mean**	**52.096**	**54.763**	**0.000**	**0.685**
	Width:depth ratio, mean	111.132	112.275	1.794	0.211		Width:depth ratio, cv	59.276	61.942	0.871	0.188		Stream power	54.356	57.023	2.260	0.221
	Stream power	111.972	113.115	2.634	0.139		Stream power	59.346	62.013	0.942	0.182		Width:depth ratio, mean	57.698	60.364	5.601	0.042
	Width:depth ratio, cv	113.368	114.511	4.030	0.069		Entrenchment, mean	59.396	62.063	0.992	0.177		Width:depth ratio, cv	58.590	61.256	6.494	0.027
	Entrenchment, cv	113.593	114.736	4.255	0.062		Entrenchment, cv	59.575	62.242	1.171	0.162		Entrenchment, cv	58.706	61.372	6.609	0.025
Temperature						Temperature						Temperature					
	Riparian vegetation	**109.797**	**110.940**	**0.000**	**0.353**		**Riparian vegetation**	**56.617**	**59.284**	**0.000**	**0.534**		**Mean summer daily temp range**	**47.383**	**50.049**	**0.000**	**0.934**
	Mean summer daily temp range	110.506	111.649	0.708	0.248		Mean summer daily temp range	58.939	61.606	2.322	0.167		Mean summer daily max temp	53.482	56.149	6.099	0.044
	Mean summer daily max temp	110.657	111.800	0.860	0.230		Canopy cover	59.067	61.733	2.449	0.157		Canopy cover	55.469	58.136	8.087	0.016
	Canopy cover	111.273	112.416	1.475	0.169		Mean summer daily max temp	59.267	61.934	2.650	0.142		Riparian vegetation	57.756	60.423	10.374	0.005
Water quality						Water quality						Water quality					
	Nitrate, mean	**105.828**	**106.971**	**0.000**	**0.812**		**Dissolved oxygen, mean**	**53.248**	**55.915**	**0.000**	**0.617**		**Specific conductance, mean**	**51.537**	**54.204**	**0.000**	**0.844**
	Dissolved oxygen, mean	110.032	111.175	4.204	0.099		Nitrate, mean	55.151	57.818	1.903	0.238		Nitrate, mean	56.284	58.951	4.747	0.079
	Specific conductance, mean	111.222	112.365	5.394	0.055		Specific conductance, mean	57.083	59.749	3.835	0.091		Dissolved oxygen, cv	58.381	61.048	6.844	0.028
	Specific conductance, cv	113.508	114.651	7.680	0.017		Dissolved oxygen, cv	59.443	62.110	6.195	0.028		Dissolved oxygen, mean	58.551	61.218	7.014	0.025
	Dissolved oxygen, cv	113.561	114.703	7.733	0.017		Specific conductance, cv	59.546	62.213	6.298	0.026		Specific conductance, cv	58.635	61.302	7.098	0.024

Appendix H.8. Fish, intolerant models with impervious cover and one additional predictor. Model selection was performed with Akaike’s Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Habitat						Habitat						Habitat					
	Large wood, volume	**129.744**	**130.887**	**0.000**	**0.180**		**Habitat unit transitions**	**78.510**	**81.177**	**0.000**	**0.253**		**Sediment, heterogeneity**	**53.985**	**56.651**	**0.000**	**0.101**
	Sediment, heterogeneity	130.539	131.682	0.795	0.121		Banks, undercut	79.906	82.573	1.396	0.126		Depositional features	54.200	56.866	0.215	0.090
	Pool habitat	130.965	132.108	1.221	0.098		Large wood, volume	80.437	83.104	1.927	0.097		Banks, eroded	54.251	56.918	0.266	0.088
	Habitat unit transitions	131.119	132.262	1.375	0.091		Pool habitat	80.637	83.304	2.127	0.087		Bankfull area, mean	54.425	57.092	0.440	0.081
	Banks, undercut	131.235	132.377	1.491	0.085		Sediment, heterogeneity	81.310	83.977	2.800	0.062		Sediment, D16	54.508	57.175	0.523	0.077
	Sediment, sorting (stnd dev)	131.895	133.038	2.151	0.061		Sediment, sorting (stnd dev)	81.419	84.085	2.909	0.059		Pool habitat	54.653	57.320	0.668	0.072
	Bankfull area, mean	132.366	133.509	2.622	0.049		Depositional features	81.832	84.499	3.322	0.048		Bankfull width, cv	54.707	57.373	0.722	0.070
	Banks, eroded	132.403	133.546	2.660	0.048		Bankfull area, mean	81.993	84.660	3.483	0.044		Embeddedness	54.935	57.602	0.950	0.063
	Bankfull width, cv	132.420	133.563	2.677	0.047		Banks, vegetated	82.153	84.820	3.643	0.041		Banks, vegetated	54.968	57.634	0.983	0.062
	Bankfull area, cv	132.442	133.585	2.699	0.047		Bankfull area, cv	82.168	84.835	3.658	0.041		Banks, undercut	55.006	57.672	1.021	0.060
	Sediment, D16	132.520	133.663	2.776	0.045		Sediment, D16	82.354	85.021	3.844	0.037		Habitat unit transitions	55.021	57.687	1.036	0.060
	Embeddedness	132.572	133.715	2.828	0.044		Embeddedness	82.458	85.125	3.948	0.035		Sediment, sorting (stnd dev)	55.049	57.715	1.064	0.059
	Banks, vegetated	132.596	133.739	2.852	0.043		Banks, eroded	82.460	85.127	3.951	0.035		Large wood, volume	55.061	57.727	1.076	0.059
	Depositional features	132.660	133.803	2.916	0.042		Bankfull width, cv	82.511	85.177	4.001	0.034		Bankfull area, cv	55.071	57.738	1.087	0.058
Flow						Flow						Flow					
	Entrenchment, cv	**131.397**	**132.540**	**0.000**	**0.324**		**Width:depth ratio, mean**	**81.756**	**84.423**	**0.000**	**0.247**		**Stream power**	**54.294**	**56.961**	**0.000**	**0.237**
	Width:depth ratio, cv	132.675	133.818	1.277	0.171		Entrenchment, cv	82.136	84.802	0.379	0.205		Width:depth ratio, mean	54.359	57.026	0.065	0.230
	Entrenchment, mean	132.693	133.836	1.295	0.169		Stream power	82.281	84.947	0.524	0.190		Entrenchment, cv	54.535	57.201	0.241	0.211
	Width:depth ratio, mean	132.711	133.854	1.314	0.168		Entrenchment, mean	82.300	84.967	0.544	0.188		Width:depth ratio, cv	55.058	57.725	0.764	0.162
	Stream power	132.715	133.858	1.317	0.168		Width:depth ratio, cv	82.511	85.177	0.754	0.170		Entrenchment, mean	55.082	57.749	0.788	0.160
Temperature						Temperature						Temperature					
	Mean summer daily max temp	**109.930**	**111.073**	**0.000**	**1.000**		**Mean summer daily max temp**	**66.639**	**69.306**	**0.000**	**0.982**		**Mean summer daily max temp**	**44.859**	**47.526**	**0.000**	**0.978**
	Mean summer daily temp range	129.976	131.119	20.045	0.000		Mean summer daily temp range	74.749	77.416	8.110	0.017		Canopy cover	54.101	56.768	9.242	0.010
	Riparian vegetation	132.397	133.540	22.467	0.000		Riparian vegetation	82.061	84.728	15.422	0.000		Riparian vegetation	55.030	57.696	10.170	0.006
	Canopy cover	132.712	133.855	22.781	0.000		Canopy cover	82.470	85.137	15.831	0.000		Mean summer daily temp range	55.082	57.749	10.222	0.006
Water quality						Water quality						Water quality					
	Nitrate, mean	**129.793**	**130.935**	**0.000**	**0.345**		**Nitrate, mean**	**80.350**	**83.017**	**0.000**	**0.295**		**Dissolved oxygen, mean**	**53.589**	**56.256**	**0.000**	**0.326**
	Dissolved oxygen, cv	130.331	131.474	0.538	0.264		Dissolved oxygen, cv	80.492	83.159	0.142	0.275		Specific conductance, cv	54.668	57.335	1.080	0.190
	Specific conductance, mean	131.259	132.401	1.466	0.166		Specific conductance, cv	81.345	84.012	0.995	0.180		Specific conductance, mean	54.896	57.563	1.307	0.169
	Specific conductance, cv	131.829	132.972	2.036	0.125		Specific conductance, mean	81.725	84.391	1.374	0.149		Dissolved oxygen, cv	55.003	57.669	1.414	0.161
	Dissolved oxygen, mean	132.268	133.411	2.475	0.100		Dissolved oxygen, mean	82.486	85.153	2.136	0.101		Nitrate, mean	55.081	57.748	1.492	0.154

APPENDIX I:

EQUALLY PLAUSIBLE MODELS FROM ALL-SUBSETS GLMS AND GLMMS WITH REACH-SCALE PREDICTORS

Appendix I. Equally plausible models from all subsets modeling. All subsets of GLMs and GLMMs were run with impervious and the top four predictors from each predictor category for each biotic response variable and for each impervious band. Equally plausible models are those within < 2 ΔAICc units. The variance explained by each model was calculated with R^2 for macroinvertebrate richness and macroinvertebrate tolerance (GLM with Gaussian distribution); pseudo-R^2 for fish richness (GLM with Poisson distribution); and conditional-R^2 for relative abundances of macroinvertebrate flow traits, fluvial fish, coldwater macroinvertebrates, coldwater fishes, and intolerant fishes (GLMM with binomial distribution).

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Richness									
Macroinvertebrate richness									
	Both bands								
		1	IC.2011 + Sed.D16 + Nitrate.mean	40	4	272.182	0.000	0.102	0.286
		2	Sed.D16 + Temp.Avg.summ.max + Nitrate.mean	40	4	272.646	0.464	0.081	0.278
		3	Nitrate.mean	40	2	272.649	0.467	0.080	0.185
		4	Temp.Avg.summ.max + Nitrate.mean	40	3	272.687	0.505	0.079	0.231
		5	Sed.D16 + Nitrate.mean	40	3	273.051	0.869	0.066	0.224
		6	IC.2011 + Nitrate.mean	40	3	273.110	0.928	0.064	0.223
		7	IC.2011 + Sed.D16 + Temp.Avg.summ.max + Nitrate.mean	40	5	273.269	1.087	0.059	0.313
		8	IC.2011 + Sed.D16 + Temp.Avg.summ.max	40	4	273.874	1.692	0.044	0.255
	Low band								
		1	Nitrate.mean	20	2	133.984	0.000	0.176	0.269
		2	Canopy + Nitrate.mean	20	3	134.661	0.677	0.126	0.342
		3	ENTRENCH.mean + Nitrate.mean	20	3	135.698	1.714	0.075	0.307
		4	Banks.dep + Nitrate.mean	20	3	135.792	1.808	0.071	0.304
		5	Banks.dep + Canopy	20	3	135.850	1.866	0.069	0.302
	High band								
		1	IC.2011 + Sed.D16 + Temp.Avg.summ.max	20	4	133.025	0.000	0.162	0.590
		2	IC.2011 + Sed.D16 + Cond.mean	20	4	133.072	0.047	0.158	0.589
		3	IC.2011 + Sed.D16 + Temp.Avg.summ.max + Cond.mean	20	5	133.186	0.161	0.150	0.655
		4	Sed.D16 + Temp.Avg.summ.max + Cond.mean	20	4	134.209	1.184	0.090	0.565
		5	IC.2011 + Sed.D16	20	3	135.015	1.990	0.060	0.469
Fish richness									
	Both bands								
		1	IC.2011 + ENTRENCH.cv	40	3	175.352	0.000	0.113	0.269
		2	IC.2011 + ENTRENCH.cv + DO.mean	40	4	175.352	0.000	0.113	0.334
		3	IC.2011 + Banks.dep + ENTRENCH.cv + DO.mean	40	5	176.136	0.784	0.076	0.383
		4	IC.2011 + Banks.dep + ENTRENCH.cv	40	4	176.287	0.935	0.071	0.310
		5	IC.2011 + DO.mean	40	3	176.421	1.069	0.066	0.241
		6	IC.2011 + Banks.dep + DO.mean	40	4	176.646	1.294	0.059	0.300
		7	ENTRENCH.cv + DO.mean	40	3	177.153	1.801	0.046	0.222
		8	Banks.dep + ENTRENCH.cv + DO.mean	40	4	177.275	1.923	0.043	0.284
	Low band								
		1	Banks.veg	20	2	86.183	0.000	0.190	0.389
		2	Banks.veg + DO.mean	20	3	86.774	0.591	0.141	0.555
		3	Banks.veg + W.D.RATIO.mean	20	3	87.517	1.334	0.097	0.499
		4	DO.mean	20	2	87.977	1.794	0.077	0.254
	High band								
		1	Banks.dep + ENTRENCH.cv	20	3	83.277	0.000	0.193	0.612
		2	ENTRENCH.cv	20	2	84.361	1.084	0.112	0.431
		3	ENTRENCH.cv + Cond.mean	20	3	84.829	1.552	0.089	0.540
		4	Banks.dep + ENTRENCH.cv + Cond.mean	20	4	85.032	1.755	0.080	0.678

Appendix I, continued

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Flow traits									
Macroinvertebrate flow traits									
	Both bands								
		1	AREA.BF.cv + ENTRENCH.mean + Temp.Avg.summ.max + (1|UniqueID)	40	5	189.059	0.000	0.137	0.084
		2	AREA.BF.cv + Temp.Avg.summ.max + (1|UniqueID)	40	4	189.206	0.147	0.127	0.069
		3	AREA.BF.cv + Temp.Avg.summ.max + Nitrate.mean + (1|UniqueID)	40	5	190.089	1.030	0.082	0.078
		4	AREA.BF.cv + ENTRENCH.mean + Temp.Avg.summ.max + Nitrate.mean + (1|UniqueID)	40	6	190.657	1.598	0.062	0.089
		5	AREA.BF.cv + Nitrate.mean + (1|UniqueID)	40	4	190.732	1.673	0.059	0.061
		6	ENTRENCH.mean + Temp.Avg.summ.max + (1|UniqueID)	40	4	190.982	1.924	0.052	0.059
		7	Temp.Avg.summ.max + (1|UniqueID)	40	3	191.055	1.996	0.050	0.044
	Low band								
		1	Nitrate.mean + (1|UniqueID)	20	3	85.926	0.000	0.175	0.048
		2	Banks.dep + Nitrate.mean + (1|UniqueID)	20	4	86.496	0.570	0.132	0.062
		3	Banks.dep + (1|UniqueID)	20	3	86.835	0.909	0.111	0.041
		4	Banks.dep + Temp.Avg.summ.max + (1|UniqueID)	20	4	87.480	1.554	0.081	0.056
	High band								
		1	AREA.BF.cv + Power.width + Temp.Avg.summ.max + (1|UniqueID)	20	5	87.508	0.000	0.315	0.292
		2	AREA.BF.cv + Temp.Avg.summ.max + (1|UniqueID)	20	4	88.343	0.835	0.207	0.262
Fish flow traits									
	Both bands								
		1	IC.2011 + Hab.trans + DO.mean + (1|UniqueID)	40	5	167.116	0.000	0.247	0.383
		2	IC.2011 + DO.mean + (1|UniqueID)	40	4	167.966	0.850	0.162	0.328
		3	IC.2011 + Power.width + DO.mean + (1|UniqueID)	40	5	168.411	1.295	0.129	0.353
		4	IC.2011 + Riparian.basal + DO.mean + (1|UniqueID)	40	5	168.512	1.396	0.123	0.360
		5	IC.2011 + Hab.trans + Riparian.basal + DO.mean + (1|UniqueID)	40	6	169.002	1.887	0.096	0.397
	Low band								
		1	Power.width + (1|UniqueID)	20	3	93.178	0.000	0.169	0.117
		2	Sed.D16 + (1|UniqueID)	20	3	93.849	0.671	0.120	0.131
		3	Cond.mean + (1|UniqueID)	20	3	94.719	1.541	0.078	0.065
		4	Sed.D16 + Cond.mean + (1|UniqueID)	20	4	94.818	1.640	0.074	0.191
		5	Power.width + Cond.mean + (1|UniqueID)	20	4	94.966	1.788	0.069	0.153
	High band								
		1	W.D.RATIO.cv + DO.mean + (1|UniqueID)	20	4	68.475	0.000	0.369	0.601

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Thermal traits									
Macroinvertebrate thermal traits									
	Both bands								
		1	IC.2011 + Sed.D16 + Cond.mean + (1|UniqueID)	40	5	173.710	0.000	0.150	0.072
		2	IC.2011 + Sed.D16 + W.D.RATIO.mean + (1|UniqueID)	40	5	174.425	0.715	0.105	0.069
		3	IC.2011 + Sed.D16 + (1|UniqueID)	40	4	174.529	0.819	0.100	0.055
		4	IC.2011 + Sed.D16 + W.D.RATIO.mean + Cond.mean + (1|UniqueID)	40	6	174.702	0.993	0.092	0.080
		5	IC.2011 + W.D.RATIO.mean + (1|UniqueID)	40	4	175.167	1.457	0.073	0.051
		6	IC.2011 + W.D.RATIO.mean + Cond.mean + (1|UniqueID)	40	5	175.710	2.000	0.055	0.061
	Low band								
		1	IC.2011 + WIDTH.BF.cv + Power.width + Cond.cv + (1|UniqueID)	20	6	84.674	0.000	0.438	0.144
	High band								
		1	W.D.RATIO.mean + (1|UniqueID)	20	3	83.909	0.000	0.147	0.096
		2	W.D.RATIO.mean + Cond.mean + (1|UniqueID)	20	4	84.640	0.731	0.102	0.112
		3	LWD.volume + W.D.RATIO.mean + (1|UniqueID)	20	4	84.880	0.971	0.091	0.123
		4	LWD.volume + (1|UniqueID)	20	3	85.112	1.203	0.081	0.098
		5	IC.2011 + LWD.volume + Cond.mean + (1|UniqueID)	20	5	85.429	1.520	0.069	0.137
		6	IC.2011 + W.D.RATIO.mean + Cond.mean + (1|UniqueID)	20	5	85.544	1.635	0.065	0.128
Fish thermal traits									
	Both bands								
		1	IC.2011 + LWD.volume + Riparian.basal + (1|UniqueID)	40	5	152.589	0.000	0.123	0.284
		2	LWD.volume + Riparian.basal + (1|UniqueID)	40	4	152.710	0.121	0.116	0.243
		3	IC.2011 + LWD.volume + Riparian.basal + DO.mean + (1|UniqueID)	40	6	152.836	0.248	0.109	0.328
		4	LWD.volume + Riparian.basal + DO.mean + (1|UniqueID)	40	5	153.047	0.458	0.098	0.282
		5	IC.2011 + LWD.volume + DO.mean + (1|UniqueID)	40	5	153.811	1.222	0.067	0.275
		6	IC.2011 + LWD.volume + (1|UniqueID)	40	4	154.033	1.444	0.060	0.228
		7	LWD.volume + DO.mean + (1|UniqueID)	40	4	154.496	1.907	0.047	0.223
	Low band								
		1	LWD.volume + (1|UniqueID)	20	3	98.657	0.000	0.244	0.200
		2	LWD.volume + Temp.Avg.summ.range + (1|UniqueID)	20	4	99.994	1.338	0.125	0.246
		3	IC.2011 + LWD.volume + (1|UniqueID)	20	4	100.069	1.412	0.121	0.242
	High band								
		1	Sed.het + Power.width + (1|UniqueID)	20	4	52.065	0.000	0.320	0.648
		2	IC.2011 + Sed.het + Power.width + (1|UniqueID)	20	5	53.832	1.767	0.132	0.620

Appendix I, continued

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Tolerance									
Macroinvertebrate tolerance index									
	Both bands								
		1	Embed.avg + Riparian.basal + Nitrate.mean	40	4	92.924	0.000	0.182	0.485
		2	IC.2011 + Embed.avg + Riparian.basal + Nitrate.mean	40	5	92.948	0.024	0.180	0.517
		3	Embed.avg + ENTRENCH.mean + Riparian.basal + Nitrate.mean	40	5	93.624	0.700	0.128	0.509
		4	IC.2011 + Embed.avg + ENTRENCH.mean + Nitrate.mean	40	5	93.922	0.998	0.110	0.505
		5	IC.2011 + Embed.avg + Nitrate.mean	40	4	93.948	1.024	0.109	0.471
		6	Embed.avg + ENTRENCH.mean + Nitrate.mean	40	4	94.117	1.193	0.100	0.469
		7	IC.2011 + Embed.avg + ENTRENCH.mean + Riparian.basal + Nitrate.mean	40	6	94.473	1.549	0.084	0.532
	Low band								
		1	IC.2011 + Embed.avg + DO.mean	20	4	48.378	0.000	0.366	0.614
		2	IC.2011 + Embed.avg	20	3	49.050	0.672	0.262	0.533
	High band								
		1	IC.2011 + Cond.mean + Embed.avg	20	4	40.667	0.000	0.205	0.705
		2	Cond.mean + Embed.avg	20	3	40.873	0.206	0.185	0.651
		3	IC.2011 + Temp.Avg.summ.range + Cond.mean + Embed.avg	20	5	41.100	0.433	0.165	0.749
		4	IC.2011 + Temp.Avg.summ.range + Embed.avg	20	4	42.001	1.334	0.105	0.685
		5	Temp.Avg.summ.range + Cond.mean + Embed.avg	20	4	42.491	1.824	0.082	0.677
Fish intolerance									
	Both bands								
		1	Temp.Avg.summ.max + (1|UniqueID)	40	3	108.630	0.000	0.274	0.471
		2	ENTRENCH.cv + Temp.Avg.summ.max + (1|UniqueID)	40	4	110.008	1.378	0.137	0.491
		3	Temp.Avg.summ.max + Nitrate.mean + (1|UniqueID)	40	4	110.165	1.535	0.127	0.479
	Low band								
		1	IC.2011 + Temp.Avg.summ.max + (1|UniqueID)	20	4	69.306	0.000	0.342	0.556
		2	Temp.Avg.summ.max + (1|UniqueID)	20	3	70.435	1.130	0.194	0.481
	High band								
		1	Temp.Avg.summ.max + DO.mean + (1|UniqueID)	20	4	43.731	0.000	0.330	0.664
		2	Temp.Avg.summ.max + (1|UniqueID)	20	3	44.492	0.761	0.226	0.570

APPENDIX J:

LAND COVER CLASSIFICATIONS

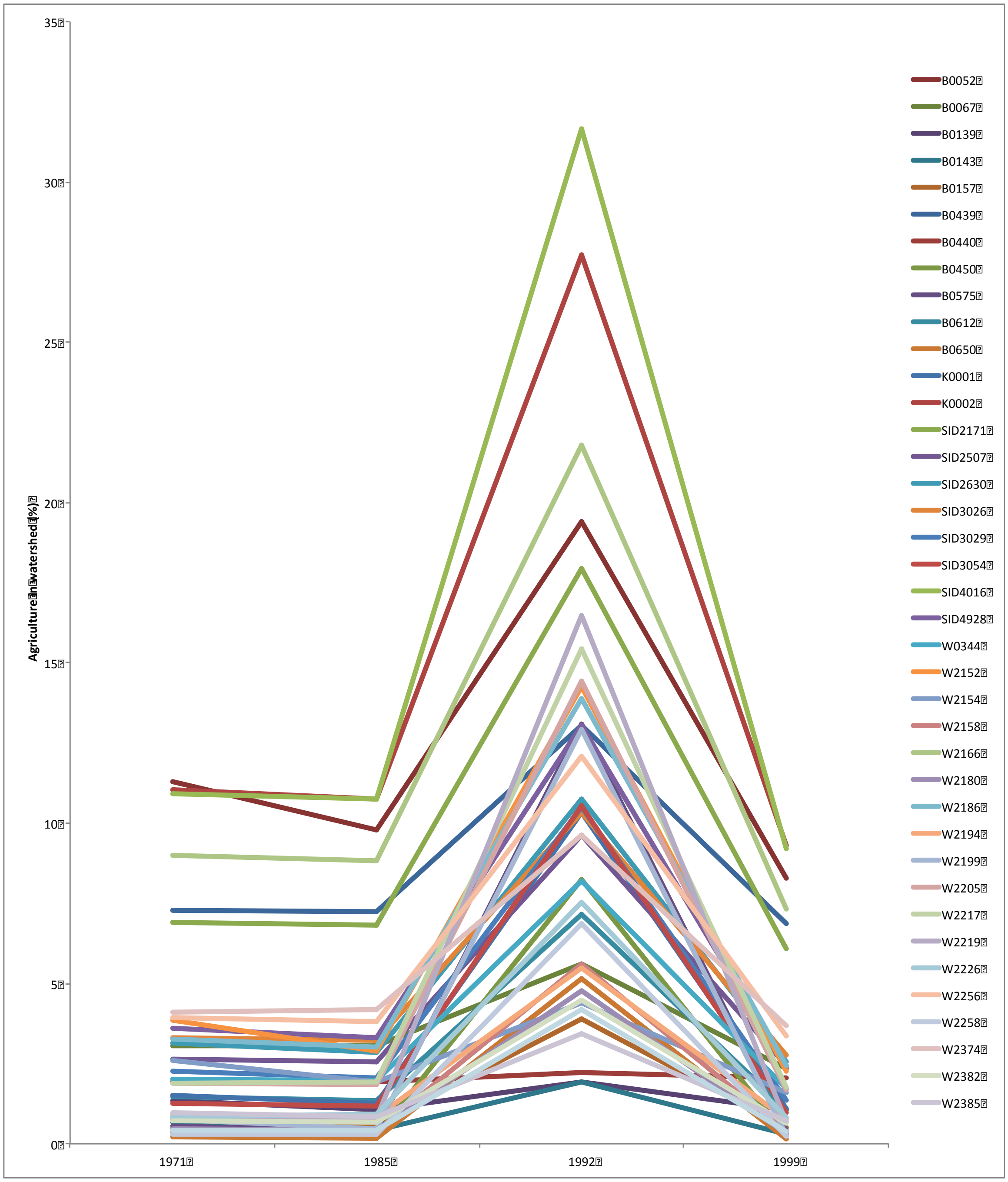
Appendix J.1. National Land Cover Dataset (NLCD) land use classifications with corresponding MassGIS classifications to facilitate comparisons across land use datasets collected by different agencies.

National Land Cover Dataset (2011)				National Land Cover Dataset (1992)				MassGIS (1971, 1985, 1999)			
Class	Code	Subclass	Description	Class	Code	Subclass	Description	Class	Abbrev.	Code	Description
Water	11	Open Water	Areas of open water, generally with less than 25% cover of vegetation or soil	Water	11	Open Water	Areas of open water, generally with less than 25% cover of vegetation/land cover	Water	W	20, 30	Fresh water; coastal embayment
	12	Perennial Ice/Snow	Areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover		12	Perennial Ice/Snow	Areas characterized by year-long surface cover of ice and/or snow				
Developed	21	Developed, Open Space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes		85	Urban/ Recreational Grasses	Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses	Urban Open	UO, UP, H, CM	17, 31, 33, 34	Parks; cemeteries; public & institutional greenspace; also vacant undeveloped land
								Participation Recreation	RP, RG	7,26	Golf; tennis; Playgrounds; skiing
								Spectator Recreation	RS	8	Stadiums; racetracks; Fairgrounds; drive-ins
								Water Based Recreation	RW, RSB, RM	9, 25, 29	Beaches; marinas; Swimming pools
	22	Developed, Low Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units	Developed	21	Low Intensity Residential	Areas with a mixture of constructed materials and vegetation. Constructed materials account for 30% to 80% of the cover. Vegetation may account for 20% to 70 % of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas	Residential	R3	13	Larger than 1/2 acre lots
	23	Developed, Medium Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units					Residential	R1	11	Smaller than 1/4 acre lots
								Residential	R2	12	1/4 - 1/2 acre lots
	24	Developed, High Intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover		22	High Intensity Residential	Areas highly developed where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20% of the cover. Constructed materials account for 80% to100% of the cover	Residential	R0	10	Multi-family
					23	Commercial/ Industrial/ Transportation	Areas of infrastructure (e.g. roads, railroads, etc.) and all highly developed areas not classified as High Intensity Residential	Commercial	UC	15	General urban; shopping center
								Industrial	UI	16	Light and heavy industry
								Transportation	UT, TF	18, 32	Airports; docks; divided highway; freight; storage; railroads
								Waste Disposal	UW	19	Landfills; sewage lagoons

Appendix J.1, continued.

National Land Cover Dataset (2011)				National Land Cover Dataset (1992)				MassGIS (1971, 1985, 1999)			
Class	Code	Subclass	Description	Class	Code	Subclass	Description	Class	Abbrev.	Code	Description
Forest	41	Deciduous Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change	Forest	41	Deciduous Forest	Areas dominated by trees where 75% or more of the tree species shed foliage simultaneously in response to seasonal change				
	42	Evergreen Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage		42	Evergreen Forest	Areas dominated by trees where 75% or more of the tree species maintain their leaves all year. Canopy is never without green foliage				
	43	Mixed Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover		43	Mixed Forest	Areas dominated by trees where neither deciduous nor evergreen species represent more than 75% of the cover present	Forest	F	3, 37	Forest
Planted/ Cultivated	81	Pasture/Hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation	Planted/ Cultivated	81	Pasture/Hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops	Pasture	AP	2	Extensive agriculture
	82	Cultivated Crops	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled		82	Row Crops	Areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton	Cropland	AC	1	Intensive agriculture
					83	Small Grains	Areas used for the production of graminoid crops such as wheat, barley, oats, and rice				
					84	Fallow	Areas used for the production of crops that do not exhibit visible vegetation as a result of being tilled in a management practice that incorporates prescribed alternation between cropping and tillage				
Wetlands	90	Woody Wetlands	Areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water	Wetlands	91	Woody Wetlands	Areas where forest or shrubland vegetation accounts for 25% to 100% of the cover and the soil or substrate is periodically saturated with or covered with water				
	95	Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water		92	Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for 75% to 100% of the cover and the soil or substrate is periodically saturated with or covered with water	Wetland	FW	4	Nonforested freshwater wetland
								Salt Wetland	SW, TSM, ISM	14, 27, 28	Salt marsh

Appendix J.2 Agricultural time series for historical data available through 30-m resolution NLCD (1992) and 1-m resolution MassGIS (1971, 1985, 1999).



APPENDIX K:

WATERSHED-SCALE VARIABLES AND CODES

Appendix K.1. Watershed codes and descriptions for each predictor category of natural characteristics, land cover, flow alteration, and other urban measures.

Category	Code	Description
Natural characteristics		
	Area.sqkm	Drainage area
	ElevBasin.m	Elevation, basin
	ElevPP.m	Elevation, site
	SandGravel_pct	Sand and gravel
	Precip.mean.mm	Precipitation, mean
	TMax.maxC	Max annual monthly max temp
	TMax.meanC	Mean annual monthly max temp
	TMin.minC	Min annual monthly min temp
	TMin.meanC	Mean annual monthly min temp
Land cover		
	Open Water, 2011	
	Developed, 2011	
	Forest, 2011	
	Agriculture, 2011	
	Wetland, 2011	
	Open Water, buffer, 2011	
	Developed, buffer, 2011	
	Forest, buffer, 2011	
	Agriculture, buffer, 2011	
	Wetland, buffer, 2011	
	Open Water, 2006	
	Developed, 2006	
	Forest, 2006	
	Agriculture, 2006	
	Wetland, 2006	
	Agriculture, 1992	

Category	Code	Description
Flow alteration		
	Dams	Dams, total
	DamDen.sqkm	Dams, per drainage area
	Dams.strmkm	Dams, per stream length
	UnDamLFPDistTOT_km	Longest undammed flow path
	DamUS_N0Y1	Dams, upstream YN
	JunUnalt.cms	Flow unaltered, Jun
	JulUnalt.cms	Flow unaltered, Jul
	AugUnalt.cms	Flow unaltered, Aug
	SepUnalt.cms	Flow unaltered, Sep
	JunAlt.cms	Flow altered, Jun
	JulAlt.cms	Flow altered, Jul
	AugAlt.cms	Flow altered, Aug
	SeptAlt.cms	Flow altered, Sep
	JunPctDif	Flow percent dif, Jun
	JulPctDif	Flow percent dif, Jul
	AugPctDif	Flow percent dif, Aug
	SeptPctDif	Flow percent dif, Sep
	MeanPctDif	Flow percent dif, mean
Other urban		
	IC.2011	Impervious, 2011 NLCD
	IC.2006	Impervious, 2006 NLCD
	IC.06.11.dif	Impervious, 2006 to 2011 dif
	IC.MassGIS	Impervious, 2005 MassGIS
	pctImp.Buffer.10m	Impervious, buffer, 10m
	pctImp.Buffer.2011	Impervious, buffer, 2011 NLCD
	PopDen.sqkm	Population density
	HousDen.sqkm	Housing density
	RoadDen.km.sqkm	Road density
	RoadCrossings	Road crossings, total
	RoadCrossings.sqkm	Road crossings, density
	FL0.5	Flow length, wgt 0.5
	FL1	Flow length, wgt 1.0
	FL1.5	Flow length, wgt 1.5
	FL2	Flow length, wgt 2.0
	GLR0.5	Gradient:length ratio, wgt 0.5
	GLR1	Gradient:length ratio, wgt 1.0
	GLR1.5	Gradient:length ratio, wgt 1.5
	GLR2	Gradient:length ratio, wgt 2.0

Appendix K.2. Watershed variables for each site within the natural characteristics predictor category. Codes are referenced in Appendix K.1.

UniqueID	Area.sqkm	ElevBasin.m	ElevPP.m	SandGravel _pct	Precip.mean. mm	TMax. maxC	TMax. meanC	TMin. minC	TMin. meanC
B0052	9.00	75.66	48.30	5.02	1252.91	15.48	15.35	3.83	4.13
B0067	35.59	60.52	35.13	55.55	1233.50	15.73	15.61	3.16	3.57
B0139	6.47	85.34	56.10	51.08	1235.53	15.44	15.26	4.11	4.18
B0143	11.66	85.12	58.52	73.43	1244.51	15.44	15.26	4.03	4.18
B0157	31.61	48.01	25.57	22.51	1183.10	15.15	15.02	2.97	3.36
B0439	43.86	17.51	4.88	72.48	1214.28	14.89	14.66	4.08	4.33
B0440	5.85	22.74	12.29	72.95	1222.57	15.09	14.93	3.88	3.98
B0450	16.12	336.49	296.26	25.75	1191.56	13.37	13.17	0.59	1.30
B0575	22.71	88.06	37.78	69.89	1231.48	15.87	15.44	2.47	2.98
B0612	9.23	68.53	37.24	43.33	1207.41	15.60	15.37	3.87	3.99
B0650	18.39	259.24	130.83	22.50	1230.72	14.72	13.83	1.49	1.87
K0001	18.18	98.90	66.42	65.61	1198.64	15.58	15.29	2.67	3.16
K0002	57.98	80.08	32.25	60.20	1173.40	15.74	15.37	2.38	2.86
SID2171	9.24	97.16	64.16	34.58	1196.91	14.97	14.81	1.89	2.10
SID2507	5.26	53.41	37.25	79.79	1192.19	15.31	15.27	3.50	3.61
SID2630	66.33	104.72	56.11	25.91	1231.61	15.69	15.26	2.57	2.79
SID3026	51.96	273.99	198.51	3.34	1247.70	14.13	13.53	2.38	2.87
SID3029	27.28	245.64	163.18	2.60	1255.81	14.46	13.85	2.31	2.81
SID3054	13.75	322.43	213.25	29.00	1236.08	14.16	13.23	1.23	1.59
SID4016	10.11	98.33	67.09	29.29	1196.30	15.08	14.90	2.13	2.29
SID4928	8.22	125.03	91.05	22.76	1220.99	15.13	14.81	2.54	2.62
W0344	24.17	49.25	2.33	9.55	1247.21	15.48	15.41	5.58	5.81
W2152	16.50	82.72	60.06	16.19	1224.53	15.68	15.51	2.90	3.05
W2154	6.69	58.24	35.29	18.58	1202.24	15.63	15.52	3.50	3.74
W2158	22.40	363.77	299.74	19.44	1262.64	13.28	12.95	1.00	1.71
W2166	6.37	272.88	197.82	0.00	1229.44	14.10	13.61	1.85	2.12
W2180	27.37	226.95	111.45	10.86	1253.29	14.80	13.98	2.05	2.33
W2186	37.80	128.00	84.74	37.98	1220.58	15.03	14.76	2.05	2.28
W2194	45.81	323.82	237.17	11.64	1228.04	13.72	13.25	0.63	1.20
W2199	6.80	275.70	216.27	39.56	1174.68	14.10	13.61	1.02	1.19
W2205	21.38	120.50	73.80	15.82	1210.12	15.09	14.79	2.40	2.56
W2217	8.78	235.78	188.24	13.58	1254.67	14.16	14.00	2.35	2.49
W2219	15.72	115.71	47.14	43.37	1209.93	15.55	15.18	1.41	2.62
W2226	21.60	247.32	163.40	24.02	1284.48	14.39	13.79	2.01	2.28
W2256	28.66	507.32	319.35	8.67	1215.51	12.93	12.05	-0.22	0.95
W2258	72.13	502.44	349.58	19.48	1296.11	12.91	12.01	0.46	0.94
W2374	21.70	15.46	2.68	45.49	1252.66	15.38	15.17	5.22	5.47
W2382	11.54	38.40	27.42	57.24	1254.92	15.51	15.45	5.00	5.25
W2385	12.49	52.35	11.37	15.37	1243.41	15.43	15.22	4.62	4.73
W2453	6.66	173.42	76.96	48.67	1188.57	14.83	14.25	0.77	1.63

Appendix K.3. Watershed variables for each site within the land cover predictor category. Codes are referenced in Appendix K.1.

UniqueID	OpenWater. 2011	Developed. 2011	Forest. 2011	Agriculture. 2011	Wetland. 2011	OpenWater. Buffer.2011	Developed. Buffer.2011	Forest. Buffer.2011	Agriculture. Buffer.2011	Wetland. Buffer.2011	OpenWater. 2006	Developed. 2006	Forest. 2006	Agriculture. 2006	Wetland. 2006	Agriculture. 1992
B0052	1.72	23.89	40.38	13.73	14.67	3.28	13.55	31.73	17.60	29.02	1.72	23.89	40.69	13.88	14.67	19.42
B0067	2.50	36.89	36.42	3.39	19.77	4.39	21.33	31.56	4.65	36.19	2.48	31.29	39.71	4.86	20.06	5.61
B0139	0.00	24.49	56.66	0.32	17.16	0.00	15.37	47.48	0.00	35.83	0.00	24.32	56.83	0.32	17.16	1.93
B0143	13.78	29.91	40.83	0.43	13.66	17.64	18.95	38.85	0.76	22.53	13.78	29.91	40.83	0.43	13.66	1.93
B0157	1.51	23.84	44.91	2.66	26.21	2.68	15.47	34.44	2.74	43.85	1.52	22.73	45.65	2.88	26.27	3.89
B0439	3.49	28.61	31.84	11.54	21.96	6.62	20.70	24.21	9.17	37.45	3.49	28.04	32.22	11.74	21.97	13.03
B0440	0.00	10.13	48.65	1.20	39.36	0.00	5.63	31.05	0.85	62.28	0.00	10.13	48.65	1.20	39.36	2.23
B0450	0.60	11.30	63.51	3.03	20.12	1.43	12.37	45.10	1.22	39.26	0.60	11.30	64.43	3.09	20.12	8.25
B0575	4.04	33.58	45.81	3.45	7.22	7.46	29.30	41.80	3.92	13.75	4.10	31.75	47.56	3.79	7.27	13.08
B0612	0.05	33.36	49.95	5.05	10.86	0.26	28.55	43.86	6.68	19.67	0.11	29.33	52.61	6.05	11.03	7.17
B0650	1.14	10.98	75.02	1.33	9.17	2.44	15.28	61.17	1.18	18.36	1.14	10.85	75.47	1.33	9.17	5.15
K0001	0.43	33.99	41.66	4.43	15.31	0.76	30.44	34.53	4.93	27.18	0.43	33.14	43.58	4.62	15.38	10.32
K0002	0.45	28.68	32.44	14.27	18.60	0.97	25.55	22.50	14.12	32.54	0.45	28.14	32.71	14.52	18.64	27.74
SID2171	0.50	12.61	57.13	14.33	13.71	1.06	8.82	51.25	10.94	27.51	0.50	12.61	57.43	14.33	13.71	17.95
SID2507	1.54	28.54	39.62	8.99	18.46	3.54	18.62	30.98	11.46	32.40	1.54	26.11	41.56	9.43	18.51	9.61
SID2630	1.18	24.05	51.12	6.50	12.41	2.37	15.85	45.50	6.84	25.26	1.18	21.88	51.91	7.44	12.44	10.74
SID3026	6.66	15.08	57.44	5.45	14.53	11.87	9.68	49.56	2.12	26.20	6.66	14.16	58.00	5.89	14.54	10.33
SID3029	1.44	10.83	65.21	7.23	13.90	3.06	10.94	56.35	3.15	25.86	1.44	10.72	65.47	7.38	13.90	10.52
SID3054	3.28	28.23	47.13	5.29	13.21	6.43	27.74	38.18	4.20	22.10	3.28	28.23	48.36	5.34	13.21	10.54
SID4016	0.36	25.25	29.49	20.35	19.13	0.75	16.28	25.03	14.44	37.10	0.36	23.80	29.59	21.66	19.13	31.64
SID4928	0.00	26.09	45.98	2.82	20.41	0.00	10.02	38.95	4.91	41.51	0.00	21.37	48.21	4.85	20.93	13.06
W0344	0.00	23.83	40.77	2.76	28.91	0.00	20.10	32.91	0.31	41.84	0.00	23.65	40.96	2.82	28.93	8.18
W2152	0.53	32.34	39.79	6.78	18.66	1.05	23.61	29.76	9.60	34.19	0.53	31.33	40.36	7.17	18.84	14.24
W2154	0.34	15.29	59.44	4.18	20.07	0.63	11.57	47.46	4.37	35.07	0.34	15.29	59.44	4.25	20.07	4.38
W2158	4.43	7.33	72.39	5.32	8.92	8.97	8.86	57.83	5.64	18.41	4.43	7.29	73.22	5.43	8.92	5.59
W2166	0.18	10.67	65.60	15.76	6.50	0.89	8.30	66.58	12.14	10.86	0.18	10.67	65.83	15.76	6.50	21.77
W2180	5.63	23.02	63.80	0.93	5.76	11.00	23.76	50.96	1.32	12.41	5.63	22.38	64.45	1.07	5.77	4.79
W2186	6.14	20.63	43.24	11.89	12.98	10.54	14.31	39.55	8.68	24.02	6.16	20.07	43.83	12.29	12.99	13.89
W2194	3.77	9.59	70.80	5.14	9.21	6.95	7.67	65.03	2.91	16.88	3.72	9.34	71.75	5.29	9.28	5.48
W2199	0.00	20.47	61.61	1.88	14.32	0.00	24.00	50.49	1.79	23.19	0.00	20.47	62.72	2.08	14.12	12.91
W2205	4.08	11.99	61.81	8.82	11.40	7.41	10.77	52.91	5.65	22.06	4.08	11.99	61.97	8.82	11.40	14.43
W2217	2.78	14.31	58.80	11.19	10.42	5.28	16.87	49.30	7.69	19.26	2.79	13.78	59.91	11.19	10.42	15.42
W2219	0.18	17.20	61.01	8.66	9.40	0.43	13.12	52.02	10.38	20.54	0.18	16.62	62.17	8.89	9.40	16.49
W2226	0.17	5.17	71.33	7.59	14.55	0.38	3.90	61.18	4.83	28.81	0.17	5.17	71.45	7.61	14.55	7.52
W2256	0.17	4.74	83.07	7.07	1.83	0.46	5.99	74.08	11.82	5.19	0.17	4.35	83.81	7.11	1.83	12.08
W2258	2.75	7.72	67.86	5.42	13.48	5.26	8.58	57.31	4.06	22.72	2.75	7.70	68.30	5.43	13.47	6.86
W2374	1.02	7.72	45.89	14.09	28.50	1.64	5.93	36.80	15.05	39.43	0.93	7.72	46.01	14.20	28.50	9.62
W2382	1.97	8.34	68.67	3.98	14.28	3.09	5.94	63.40	4.26	21.82	1.97	8.34	69.05	3.98	14.28	4.49
W2385	0.80	31.56	53.35	0.00	13.69	1.64	22.20	49.17	0.00	26.50	0.66	30.18	54.62	0.00	13.82	3.45
W2453	4.61	7.43	80.81	0.26	1.31	9.26	9.41	76.35	0.06	2.60	4.61	7.43	83.07	0.26	1.31	4.18

Appendix K.4. Watershed variables for each site within the flow alteration predictor category. Codes are referenced in Appendix K.1.

UniqueID	Dams	DamDen. sqkm	Dams.strm km	UnDamLFP DistTOT_km	DamUS_ N0Y1	JunUnalt. cms	JulUnalt. cms	AugUnalt. cms	SepUnalt. cms	JunAlt. cms	JulAlt. cms	AugAlt. cms	SeptAlt. cms	JunPctDif	JulPctDif	AugPctDif	SeptPctDif	MeanPctDif
B0052	1	0.75	0.17	11.22	0	0.067	0.018	0.019	0.017	0.065	0.017	0.018	0.016	-2.746	-8.906	-6.959	-5.845	-0.360
B0067	4	0.75	0.21	25.15	1	0.287	0.097	0.109	0.104	0.253	0.066	0.083	0.083	-11.966	-32.178	-23.598	-20.028	-2.125
B0139	0	0.00	0.00	6.69	0	0.053	0.017	0.019	0.018	0.037	0.000	0.003	0.003	-30.796	-99.717	-83.945	-83.054	-8.750
B0143	4	2.30	0.45	3.92	1	0.086	0.033	0.038	0.036	0.083	0.031	0.036	0.035	-2.790	-6.766	-4.550	-2.850	-0.286
B0157	3	0.64	0.17	3.21	1	0.267	0.092	0.060	0.045	0.244	0.072	0.044	0.033	-8.461	-21.550	-26.674	-26.348	-1.402
B0439	2	0.31	0.07	16.72	1	0.404	0.167	0.117	0.090	0.394	0.156	0.107	0.080	-2.599	-6.371	-8.281	-10.439	-28.968
B0440	0	0.00	0.00	6.66	0	0.050	0.019	0.012	0.009	0.049	0.018	0.012	0.008	-2.197	-5.086	-6.318	-6.561	-0.345
B0450	4	1.66	0.60	21.54	1	0.110	0.063	0.039	0.043	0.053	0.013	0.000	0.013	-51.463	-79.459	-100.000	-69.046	-5.546
B0575	2	0.59	0.31	17.72	1	0.152	0.079	0.057	0.057	0.217	0.117	0.118	0.129	42.753	47.616	108.165	123.882	16.927
B0612	0	0.00	0.00	21.38	0	0.068	0.025	0.021	0.020	0.057	0.016	0.013	0.014	-15.905	-37.484	-36.997	-29.013	-2.026
B0650	5	1.82	0.61	3.66	1	0.119	0.068	0.059	0.047	0.075	0.029	0.027	0.024	-37.077	-56.774	-53.403	-49.668	-3.852
K0001	4	1.48	0.47	8.53	1	0.161	0.073	0.047	0.043	0.162	0.074	0.047	0.045	0.142	0.616	1.608	2.487	0.365
K0002	9	1.04	0.34	11.31	1	0.522	0.231	0.153	0.144	0.522	0.231	0.154	0.145	-0.005	0.145	0.541	0.953	-0.038
SID2171	0	0.00	0.00	32.75	0	0.073	0.029	0.021	0.014	0.076	0.032	0.024	0.017	3.973	9.988	13.682	21.225	1.552
SID2507	1	1.27	0.49	25.31	0	0.037	0.016	0.009	0.011	0.039	0.018	0.011	0.013	4.989	11.787	22.963	18.618	1.979
SID2630	18	1.82	0.49	12.35	1	0.520	0.197	0.168	0.161	0.520	0.198	0.170	0.164	0.002	0.367	1.112	1.875	0.211
SID3026	12	1.55	0.31	1.07	1	0.378	0.174	0.110	0.096	0.397	0.192	0.130	0.116	5.107	10.595	17.993	21.006	1.063
SID3029	5	1.23	0.24	7.61	1	0.186	0.065	0.037	0.031	0.184	0.063	0.035	0.030	-1.388	-3.481	-4.741	-3.522	-0.110
SID3054	4	1.95	0.72	4.64	1	0.087	0.050	0.047	0.032	0.087	0.050	0.047	0.032	0.049	0.262	0.509	1.138	-0.306
SID4016	0	0.00	0.00	22.28	0	0.082	0.030	0.022	0.014	0.083	0.031	0.023	0.015	1.367	3.913	5.876	9.715	0.693
SID4928	0	0.00	0.00	9.87	0	0.062	0.022	0.020	0.015	0.062	0.022	0.020	0.016	0.396	1.614	2.522	4.322	0.452
W0344	0	0.00	0.00	14.38	0	0.246	0.076	0.059	0.052	0.244	0.074	0.058	0.051	-0.808	-2.219	-2.136	-1.551	-0.079
W2152	1	0.41	0.10	11.18	1	0.122	0.038	0.032	0.030	0.079	0.001	0.001	0.009	-35.537	-98.566	-95.607	-70.621	-4.178
W2154	0	0.00	0.00	15.34	0	0.046	0.015	0.012	0.012	0.045	0.014	0.012	0.011	-2.002	-5.279	-5.478	-4.710	-0.300
W2158	5	1.50	0.52	7.78	1	0.179	0.086	0.068	0.046	0.106	0.021	0.015	0.007	-40.906	-75.297	-77.338	-84.434	-5.000
W2166	1	1.05	0.25	22.28	1	0.047	0.020	0.012	0.010	0.048	0.020	0.012	0.010	0.766	1.884	3.409	4.263	0.294
W2180	13	3.19	1.10	38.93	1	0.175	0.080	0.074	0.051	0.662	0.510	0.504	0.496	278.640	534.895	579.302	864.816	69.244
W2186	10	1.77	0.73	6.41	1	0.319	0.132	0.100	0.069	0.291	0.106	0.078	0.052	-8.992	-19.613	-21.297	-23.930	-2.114
W2194	6	0.88	0.31	4.27	1	0.294	0.153	0.143	0.101	0.201	0.071	0.076	0.052	-31.577	-53.499	-46.486	-48.653	-3.415
W2199	0	0.00	0.00	8.76	0	0.037	0.021	0.020	0.015	0.035	0.020	0.019	0.014	-5.106	-7.820	-6.669	-6.608	-0.489
W2205	10	3.14	1.03	4.81	1	0.172	0.068	0.050	0.034	0.107	0.010	0.003	0.000	-37.926	-84.587	-93.108	-100.000	-4.988
W2217	2	1.53	0.27	9.85	1	0.065	0.033	0.021	0.018	0.064	0.032	0.020	0.017	-2.030	-3.499	-4.789	-4.360	-0.298
W2219	1	0.43	0.15	14.29	1	0.139	0.059	0.037	0.034	0.122	0.037	0.018	0.015	-12.155	-36.265	-50.298	-56.590	-4.587
W2226	1	0.31	0.12	16.18	0	0.157	0.078	0.072	0.050	0.140	0.063	0.060	0.041	-10.368	-18.516	-16.638	-18.536	-1.389
W2256	2	0.47	0.15	15.92	0	0.228	0.120	0.087	0.077	0.232	0.123	0.088	0.078	1.999	2.361	1.967	2.111	0.069
W2258	6	0.56	0.21	7.54	1	0.609	0.360	0.267	0.261	0.589	0.343	0.253	0.250	-3.230	-4.807	-5.262	-4.004	-0.746
W2374	3	0.93	0.24	9.42	1	0.208	0.093	0.077	0.078	0.206	0.092	0.077	0.078	-0.743	-0.718	-0.365	0.296	-0.119
W2382	0	0.00	0.00	10.70	0	0.104	0.048	0.039	0.040	0.103	0.047	0.038	0.039	-1.112	-2.121	-2.049	-1.448	-0.152
W2385	2	1.08	0.29	1.29	1	0.079	0.026	0.022	0.027	0.079	0.027	0.022	0.028	0.627	1.991	2.608	2.237	-0.666
W2453	1	1.01	0.51	1.84	1	0.055	0.023	0.013	0.015	0.055	0.023	0.013	0.015	0.126	0.336	0.683	0.685	0.079

Appendix K.5. Watershed variables for each site within the other urban measures predictor category. Codes are referenced in Appendix K.1.

UniqueID	IC.2011	IC.2006	IC.06.11.dif	IC.MassGIS	pctImp. Buffer.10m	pctImp. Buffer.2011	PopDen. sqkm	HousDen. sqkm	RoadDen. km.sqkm	Road Crossings	RoadCrossings. sqkm	FL0.5	FL1	FL1.5	FL2	GLR0.5	GLR1	GLR1.5	GLR2
B0052	8.44	8.40	0.05	8.01	5.82	5.89	108.11	40.05	2.85	12	1.33	10.97	15.81	20.27	18.70	12.26	21.89	22.89	8.19
B0067	9.90	8.23	1.67	10.01	6.84	6.82	144.40	44.41	3.85	46	1.29	9.66	9.22	8.89	8.36	9.89	10.40	8.84	3.15
B0139	6.73	6.57	0.16	9.12	5.84	4.49	112.58	41.69	3.94	8	1.24	10.68	12.11	11.90	8.84	12.14	15.51	14.97	10.91
B0143	8.82	8.72	0.09	9.69	6.74	5.47	203.22	68.09	4.30	35	3.00	10.70	11.68	11.91	10.54	11.87	13.67	7.68	2.37
B0157	7.55	7.25	0.30	8.50	6.80	5.87	289.25	93.14	3.48	51	1.61	7.49	6.49	5.16	3.06	8.14	7.35	3.83	0.66
B0439	9.49	9.24	0.25	10.13	7.51	7.04	135.01	48.46	3.88	71	1.62	9.23	8.46	7.88	6.29	10.17	10.33	8.26	3.92
B0440	3.49	3.42	0.07	3.41	1.91	1.28	388.07	148.82	1.11	2	0.34	2.63	2.00	1.82	2.00	2.78	1.72	0.45	0.07
B0450	2.31	2.26	0.06	4.15	3.92	2.60	65.71	26.24	2.41	21	1.30	4.04	3.65	2.73	1.45	3.90	3.16	1.84	0.96
B0575	8.38	7.82	0.55	10.79	9.39	7.67	138.33	61.83	3.70	18	0.79	11.64	13.12	17.59	29.53	12.35	18.71	56.94	79.73
B0612	8.35	7.56	0.79	9.38	8.59	7.70	170.37	53.32	4.06	23	2.49	9.93	10.60	10.79	8.99	10.30	10.36	1.94	0.12
B0650	1.45	1.40	0.05	3.91	4.01	1.71	126.56	47.95	2.09	18	0.98	5.12	6.82	8.01	6.55	5.01	6.97	9.31	9.84
K0001	7.18	6.91	0.27	9.15	8.45	6.38	233.44	85.44	4.00	33	1.82	10.09	11.06	11.16	9.10	9.85	10.80	8.00	3.08
K0002	7.58	7.16	0.42	9.51	7.95	6.71	164.38	66.68	3.30	78	1.35	10.64	11.19	9.55	5.33	10.32	10.31	2.08	0.06
SID2171	3.60	3.58	0.02	6.87	4.87	2.13	157.46	57.45	3.40	13	1.41	6.73	6.49	5.93	4.47	6.95	6.09	1.31	0.07
SID2507	9.23	7.82	1.41	7.18	4.67	6.19	142.74	54.87	4.04	9	1.71	7.08	7.37	8.74	11.35	8.45	9.75	7.60	5.61
SID2630	8.01	7.29	0.73	10.18	8.13	5.85	151.55	52.99	3.27	91	1.37	10.23	11.08	13.55	19.03	10.81	13.36	23.02	44.36
SID3026	3.55	3.15	0.40	6.01	4.38	2.31	182.57	72.74	2.76	86	1.66	6.73	7.97	9.57	9.91	7.35	9.56	8.14	4.23
SID3029	2.39	2.29	0.10	5.82	5.12	2.49	106.66	38.17	2.66	64	2.35	5.88	6.01	6.55	6.94	6.08	7.52	11.09	13.53
SID3054	10.00	9.83	0.17	11.30	9.86	9.09	177.87	69.44	4.54	28	2.04	12.87	15.02	16.82	15.20	13.77	17.49	14.70	4.38
SID4016	8.77	8.29	0.48	8.95	6.45	5.12	94.37	42.81	3.44	10	0.99	8.81	8.47	7.36	4.90	9.08	6.98	0.47	0.01
SID4928	7.92	6.83	1.10	7.80	4.45	3.97	341.93	125.62	2.68	12	1.46	7.91	7.89	9.31	15.37	8.32	8.70	16.13	42.38
W0344	8.44	8.23	0.21	9.22	7.54	5.72	260.55	95.31	3.56	22	0.91	9.71	9.99	8.52	4.17	10.06	10.10	4.72	0.74
W2152	9.93	9.56	0.37	9.55	8.17	8.47	204.53	69.92	3.48	23	1.39	9.89	9.87	8.29	4.63	10.22	9.76	2.43	0.17
W2154	3.11	3.11	0.01	7.49	5.57	1.97	162.39	55.31	3.55	9	1.35	7.54	7.56	6.95	5.04	7.84	7.70	6.31	4.46
W2158	1.16	1.15	0.01	3.53	3.88	1.42	108.13	49.21	1.76	22	0.98	3.66	3.69	3.23	1.92	3.33	3.00	1.63	0.36
W2166	2.36	2.33	0.02	4.88	3.64	1.86	71.25	29.95	2.98	10	1.57	4.57	3.97	2.89	1.53	4.64	4.68	5.88	7.52
W2180	9.77	9.50	0.26	8.85	9.73	10.95	151.65	57.85	3.17	39	1.43	13.12	23.37	44.65	61.16	12.21	27.25	64.96	80.96
W2186	7.27	6.98	0.29	10.71	8.53	5.60	149.99	57.04	3.09	37	0.98	10.64	10.57	9.97	7.30	10.93	10.06	1.87	0.13
W2194	2.64	2.51	0.14	3.89	3.27	2.07	76.84	29.83	2.26	44	0.96	3.90	4.03	4.70	5.90	3.93	4.72	6.47	4.17
W2199	3.62	3.55	0.07	5.29	4.91	4.01	102.02	41.48	2.16	6	0.88	4.84	3.87	2.35	0.91	4.38	2.51	0.86	0.23
W2205	3.44	3.40	0.04	5.80	4.19	2.82	79.91	33.16	3.61	32	1.50	6.64	8.27	10.05	8.89	7.25	10.31	9.14	2.12
W2217	3.75	3.52	0.23	8.00	8.09	4.32	101.33	39.50	2.84	28	3.19	9.35	11.21	13.60	15.75	9.43	11.10	4.31	0.69
W2219	3.71	3.58	0.13	5.53	5.25	2.79	84.83	32.98	2.62	19	1.21	5.65	5.28	3.87	1.86	5.12	3.81	0.95	0.05
W2226	1.09	1.08	0.01	2.81	2.03	0.57	188.89	71.88	1.36	8	0.37	2.75	2.68	2.37	1.50	2.88	2.73	1.81	0.73
W2256	1.18	0.99	0.20	3.70	4.88	1.44	54.12	39.43	1.18	21	0.73	4.01	4.08	3.65	2.48	3.66	3.21	1.81	0.25
W2258	1.16	1.10	0.06	3.64	3.61	1.43	49.08	23.66	1.76	47	0.65	4.11	5.12	7.99	12.72	4.04	4.52	4.81	2.36
W2374	1.64	1.63	0.00	5.10	3.93	1.07	107.64	43.23	1.64	17	0.78	5.62	6.12	5.79	3.69	5.69	4.51	0.16	0.00
W2382	2.56	2.54	0.02	6.40	4.50	1.56	269.37	92.00	1.75	6	0.52	6.18	5.90	6.30	10.24	6.91	20.07	52.98	58.37
W2385	8.81	8.35	0.46	8.61	5.77	5.51	150.69	68.97	3.40	24	1.92	9.11	10.57	13.29	14.83	9.30	10.17	3.51	0.57
W2453	1.59	1.59	0.01	3.34	4.49	1.97	22.78	9.23	1.71	4	0.60	4.58	6.00	6.80	5.58	3.88	4.95	4.71	1.76

APPENDIX L:

PAIRWISE SPEARMAN RANK CORRELATION ANALYSIS FOR WATERSHED-SCALE PREDICTORS

Appendix L.1. Pairwise Spearman rank correlations for natural watershed characteristics.

	Drainage area	*Elevation, basin*	*Elevation, site*	Sand and gravel	Precipitation, mean	Max annual monthly max	*Mean annual monthly max*	Min annual monthly min	*Mean annual monthly min*
Drainage area									
Elevation, basin	0.18								
Elevation, site	0.10	**0.97**							
Sand and gravel	-0.19	-0.46	-0.46						
Precipitation, mean	0.23	0.14	0.15	-0.36					
Max annual monthly max temp	-0.07	**-0.75**	**-0.79**	0.44	-0.17				
Mean annual monthly max temp	-0.18	**-0.82**	**-0.82**	0.41	-0.15	**0.96**			
Min annual monthly min temp	-0.18	**-0.90**	**-0.86**	0.31	0.13	0.69	**0.76**		
Mean annual monthly min temp	-0.14	**-0.89**	**-0.87**	0.30	0.14	**0.71**	**0.77**	**0.98**	

Note: Highly collinear variables ($r \geq |0.7|$) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

Appendix L.2. Pairwise Spearman rank correlations for land cover variables.

	Open Water, 2011	Developed, 2011	Forest, 2011	Agriculture, 2011	Wetland, 2011	*Open Water, buffer, 2011*	*Developed, buffer, 2011*	*Forest, buffer, 2011*	*Agriculture, buffer, 2011*	*Wetland, buffer, 2011*	*Open Water, 2006*	*Developed, 2006*	*Forest, 2006*	*Agriculture, 2006*	*Wetland, 2006*
Open Water, 2011															
Developed, 2011	-0.02														
Forest, 2011	0.04	**-0.79**													
Agriculture, 2011	0.03	-0.12	-0.20												
Wetland, 2011	-0.38	0.27	-0.61	0.00											
Open Water, buffer, 2011	**1.00**	-0.03	0.06	0.03	-0.42										
Developed, buffer, 2011	0.05	**0.87**	-0.58	-0.19	0.04	0.05									
Forest, buffer, 2011	0.11	**-0.72**	**0.95**	-0.12	**-0.71**	0.13	-0.55								
Agriculture, buffer, 2011	-0.09	0.04	-0.30	**0.90**	0.02	-0.09	-0.07	-0.23							
Wetland, buffer, 2011	-0.39	0.29	-0.63	0.02	**0.97**	-0.42	0.04	**-0.72**	0.03						
Open Water, 2006	**1.00**	-0.02	0.04	0.02	-0.39	**1.00**	0.05	0.11	-0.10	-0.40					
Developed, 2006	0.00	**0.99**	**-0.79**	-0.14	0.26	-0.01	**0.89**	**-0.71**	0.00	0.27	0.00				
Forest, 2006	0.04	**-0.78**	**1.00**	-0.20	-0.62	0.06	-0.56	**0.95**	-0.29	-0.64	0.04	**-0.78**			
Agriculture, 2006	-0.01	-0.06	-0.25	**0.99**	0.02	-0.01	-0.16	-0.16	**0.91**	0.05	-0.01	-0.10	-0.24		
Wetland, 2006	-0.38	0.27	-0.61	0.00	**1.00**	-0.41	0.04	**-0.71**	0.01	**0.97**	-0.38	0.26	-0.62	0.02	

Note: Highly collinear variables (r ≥ |0.7|) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

Appendix L.3. Pairwise Spearman rank correlations for flow alteration variables.

	Dams, total	Dams, per drainage area	*Dams, per stream length*	Longest undammed flow path	*Dams, upstream YN*	*Flow unaltered, Jun*	*Flow unaltered, Jul*	*Flow unaltered, Aug*	*Flow unaltered, Sep*	*Flow altered, Jun*	*Flow altered, Jul*	Flow altered, Aug	*Flow altered, Sep*	*Flow percent dif, Jun*	*Flow percent dif, Jul*	Flow percent dif, Aug	*Flow percent dif, Sep*	*Flow percent dif, mean*
Dams, total																		
Dams, per drainage area	**0.83**																	
Dams, per stream length	**0.82**	**0.95**																
Longest undammed flow path	-0.31	-0.30	-0.28															
Dams, upstream YN	**0.78**	**0.72**	**0.72**	-0.35														
Flow unaltered, Jun	**0.71**	0.29	0.30	-0.11	0.52													
Flow unaltered, Jul	**0.74**	0.33	0.36	-0.10	0.55	**0.97**												
Flow unaltered, Aug	**0.72**	0.32	0.34	-0.10	0.49	**0.95**	**0.98**											
Flow unaltered, Sep	0.69	0.30	0.33	-0.09	0.49	**0.93**	**0.95**	**0.97**										
Flow altered, Jun	0.66	0.27	0.28	-0.01	0.46	**0.94**	**0.92**	**0.90**	**0.87**									
Flow altered, Jul	0.53	0.20	0.21	0.03	0.36	**0.78**	**0.82**	**0.79**	**0.78**	**0.89**								
Flow altered, Aug	0.53	0.19	0.19	0.02	0.30	**0.76**	**0.81**	**0.82**	**0.80**	**0.88**	**0.97**							
Flow altered, Sep	0.52	0.21	0.21	0.04	0.33	**0.74**	**0.78**	**0.78**	**0.81**	**0.85**	**0.94**	**0.97**						
Flow percent dif, Jun	-0.09	0.00	-0.01	0.25	-0.14	-0.10	-0.06	-0.11	-0.12	0.15	0.41	0.36	0.37					
Flow percent dif, Jul	-0.03	0.04	0.04	0.25	-0.10	-0.06	0.00	-0.05	-0.08	0.18	0.45	0.41	0.41	**0.99**				
Flow percent dif, Aug	-0.04	0.05	0.04	0.23	-0.11	-0.09	-0.04	-0.08	-0.09	0.15	0.42	0.39	0.40	**0.98**	**0.99**			
Flow percent dif, Sep	-0.04	0.05	0.03	0.26	-0.11	-0.08	-0.03	-0.07	-0.08	0.16	0.43	0.41	0.42	**0.98**	**0.99**	**0.99**		
Flow percent dif, mean	-0.07	0.03	0.02	0.27	-0.18	-0.13	-0.09	-0.14	-0.15	0.10	0.35	0.32	0.33	**0.92**	**0.92**	**0.94**	**0.94**	

Note: Highly collinear variables (r ≥ |0.7|) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

Appendix L.4. Pairwise Spearman rank correlations for other urban characteristics.

	Impervious, 2011 NLCD	*Impervious, 2006 NLCD*	Impervious, 2006 to 2011 dif	*Impervious, 2005 MassGIS*	Impervious, buffer, 10m	*Impervious, buffer, 2011 NLCD*	*Population density*	Housing density	Road density	Road crossings, total	Road crossings, density	*Flow length, wgt 0.5*	*Flow length, wgt 1.0*	*Flow length, wgt 1.5*	Flow length, wgt 2.0	*Gradient: length ratio, wgt 0.5*	*Gradient: length ratio, wgt 1.0*	*Gradient: length ratio, wgt 1.5*	Gradient: length ratio, wgt 2.0
Impervious, 2011 NLCD																			
Impervious, 2006 NLCD	**0.98**																		
Impervious, 2006 to 2011 dif	**0.71**	0.63																	
Impervious, 2005 MassGIS	**0.85**	**0.85**	0.66																
Impervious, buffer, 10m	**0.76**	**0.77**	0.60	**0.89**															
Impervious, buffer, 2011 NLCD	**0.90**	**0.89**	**0.72**	**0.86**	**0.87**														
Population density	0.42	0.43	0.31	0.42	0.32	0.30													
Housing density	0.40	0.41	0.33	0.39	0.29	0.26	**0.96**												
Road density	**0.77**	**0.76**	0.52	**0.81**	0.69	**0.79**	0.32	0.26											
Road crossings, total	0.27	0.26	0.44	0.42	0.38	0.41	0.06	0.02	0.29										
Road crossings, density	0.50	0.48	0.40	0.47	0.44	0.53	0.20	0.13	0.66	0.47									
Flow length, wgt 0.5	**0.81**	**0.83**	0.55	**0.92**	**0.89**	**0.85**	0.38	0.34	**0.75**	0.33	0.48								
Flow length, wgt 1.0	**0.74**	**0.76**	0.52	**0.84**	**0.83**	**0.79**	0.28	0.26	**0.71**	0.35	0.49	**0.97**							
Flow length, wgt 1.5	0.64	0.64	0.50	**0.72**	**0.70**	0.69	0.22	0.21	0.62	0.38	0.50	**0.87**	**0.94**						
Flow length, wgt 2.0	0.47	0.45	0.45	0.51	0.46	0.48	0.18	0.17	0.40	0.32	0.41	0.66	**0.73**	**0.88**					
Gradient:length ratio, wgt 0.5	**0.83**	**0.85**	0.57	**0.93**	**0.87**	**0.86**	0.35	0.32	**0.77**	0.35	0.48	**0.99**	**0.96**	**0.86**	0.66				
Gradient:length ratio, wgt 1.0	0.67	0.68	0.43	**0.78**	**0.73**	**0.71**	0.33	0.28	0.66	0.31	0.46	**0.88**	**0.89**	**0.88**	**0.81**	**0.88**			
Gradient:length ratio, wgt 1.5	0.31	0.30	0.23	0.39	0.29	0.38	0.16	0.11	0.36	0.25	0.28	0.50	0.52	0.63	**0.75**	0.52	**0.74**		
Gradient:length ratio, wgt 2.0	0.11	0.08	0.08	0.16	0.07	0.16	0.07	0.03	0.18	0.07	0.17	0.27	0.28	0.40	0.60	0.29	0.52	**0.93**	

Note: Highly collinear variables (r ≥ |0.7|) are highlighted in bold. Italicized variables were dropped from subsequent analyses.

APPENDIX M:

SINGLE-VARIABLE MODEL COMPARISON FOR WATERSHED-SCALE PREDICTORS

Appendix M.1. Macroinvertebrate richness models with total impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Sand and gravel	**276.414**	**277.557**	**0.000**	**0.269**		**Sand and gravel**	**137.449**	**140.116**	**0.000**	**0.296**		**Sand and gravel**	**143.211**	**145.878**	**0.000**	**0.224**
	Drainage area	276.540	277.683	0.126	0.253		Min annual monthly min temp	137.483	140.149	0.034	0.291		Max annual monthly max temp	143.350	146.017	0.139	0.209
	Min annual monthly min temp	276.543	277.686	0.129	0.252		Drainage area	138.900	141.567	1.452	0.143		Drainage area	143.465	146.131	0.253	0.197
	Precipitation, mean	278.127	279.270	1.713	0.114		Max annual monthly max temp	139.010	141.676	1.561	0.136		Min annual monthly min temp	143.571	146.238	0.360	0.187
	Max annual monthly max temp	278.191	279.334	1.777	0.111		Precipitation, mean	139.056	141.723	1.608	0.133		Precipitation, mean	143.598	146.265	0.386	0.184
Land cover						Land cover						Land cover					
	Agriculture, 1992	**274.729**	**275.871**	**0.000**	**0.481**		**Agriculture, 1992**	**134.602**	**137.268**	**0.000**	**0.554**		**Open Water, 2011**	**141.339**	**144.005**	**0.000**	**0.403**
	Wetland, 2011	276.579	277.722	1.851	0.191		Wetland, 2011	135.816	138.483	1.214	0.302		Agriculture, 1992	142.976	145.642	1.637	0.178
	Open Water, 2011	276.767	277.910	2.038	0.174		Agriculture, 2011	138.094	140.761	3.493	0.097		Agriculture, 2011	143.218	145.885	1.880	0.158
	Agriculture, 2011	278.293	279.436	3.565	0.081		Forest, 2011	140.759	143.426	6.158	0.025		Wetland, 2011	143.533	146.200	2.195	0.135
	Forest, 2011	278.491	279.634	3.763	0.073		Open Water, 2011	141.043	143.710	6.441	0.022		Forest, 2011	143.655	146.321	2.316	0.127
Flow alteration						Flow alteration						Flow alteration					
	Flow altered, Aug	**276.570**	**277.713**	**0.000**	**0.438**		**Flow altered, Aug**	**138.059**	**140.726**	**0.000**	**0.556**		**Flow altered, Aug**	**142.732**	**145.399**	**0.000**	**0.306**
	Flow percent dif, Aug	277.959	279.102	1.389	0.219		Longest undammed flow path	140.229	142.896	2.170	0.188		Flow percent dif, Aug	142.745	145.412	0.013	0.304
	Dams, per drainage area	278.406	279.549	1.836	0.175		Flow percent dif, Aug	140.864	143.530	2.804	0.137		Dams, per drainage area	143.600	146.267	0.868	0.198
	Longest undammed flow path	278.480	279.623	1.910	0.169		Dams, per drainage area	141.127	143.794	3.068	0.120		Longest undammed flow path	143.654	146.321	0.922	0.193
Other urban measures						Other urban measures						Other urban measures					
	Impervious, buffer, 10m-res	**274.924**	**276.066**	**0.000**	**0.350**		**Housing density**	**135.814**	**138.481**	**0.000**	**0.378**		**Housing density**	**137.501**	**140.167**	**0.000**	**0.688**
	Road crossings, total	276.682	277.824	1.758	0.145		Road crossings, density	137.143	139.810	1.329	0.194		Gradient:length ratio, wgt 2.0	142.120	144.787	4.620	0.068
	Road crossings, density	277.192	278.335	2.269	0.113		Impervious, buffer, 10m-res	137.790	140.456	1.975	0.141		Flow length, wgt 2.0	142.837	145.504	5.337	0.048
	Flow length, wgt 2.0	277.409	278.552	2.486	0.101		Road density	138.915	141.582	3.101	0.080		Impervious, buffer, 10m-res	142.857	145.524	5.356	0.047
	Road density	277.779	278.922	2.855	0.084		Flow length, wgt 2.0	139.307	141.974	3.493	0.066		Impervious, 2006 to 2011 dif	143.102	145.769	5.601	0.042
	Gradient:length ratio, wgt 2.0	277.907	279.050	2.984	0.079		Road crossings, total	139.704	142.370	3.889	0.054		Road crossings, total	143.205	145.872	5.704	0.040
	Impervious, 2006 to 2011 dif	278.168	279.311	3.245	0.069		Impervious, 2006 to 2011 dif	139.787	142.453	3.972	0.052		Road density	143.433	146.100	5.933	0.035
	Housing density	278.494	279.637	3.571	0.059		Gradient:length ratio, wgt 2.0	140.548	143.215	4.734	0.035		Road crossings, density	143.645	146.312	6.145	0.032

Appendix M.2. Fish richness models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands					
Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics					
	Drainage area	**176.435**	**177.102**	**0.000**	**0.565**
	Min annual monthly min temp	179.063	179.730	2.629	0.152
	Max annual monthly max temp	179.955	180.621	3.520	0.097
	Sand and gravel	180.021	180.688	3.587	0.094
	Precipitation, mean	180.053	180.720	3.618	0.092
Land cover					
	Forest, 2011	**177.512**	**178.178**	**0.000**	**0.375**
	Agriculture, 1992	178.204	178.871	0.693	0.265
	Agriculture, 2011	179.398	180.065	1.887	0.146
	Wetland, 2011	179.970	180.637	2.459	0.110
	Open Water, 2011	180.056	180.722	2.544	0.105
Flow alteration					
	Longest undammed flow path	**179.484**	**180.150**	**0.000**	**0.271**
	Dams, per drainage area	179.629	180.296	0.145	0.252
	Flow altered, Aug	179.648	180.315	0.164	0.249
	Flow percent dif, Aug	179.820	180.487	0.336	0.229
Other urban measures					
	Road crossings, total	**178.237**	**178.904**	**0.000**	**0.207**
	Impervious, buffer, 10m-res	178.269	178.936	0.032	0.204
	Housing density	178.717	179.384	0.480	0.163
	Flow length, wgt 2.0	179.935	180.601	1.697	0.089
	Gradient:length ratio, wgt 2.0	180.026	180.693	1.789	0.085
	Road density	180.033	180.699	1.795	0.085
	Impervious, 2006 to 2011 dif	180.049	180.715	1.811	0.084
	Road crossings, density	180.056	180.723	1.819	0.084

Very-low band					
Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics					
	Max annual monthly max temp	**90.418**	**91.918**	**0.000**	**0.285**
	Drainage area	90.909	92.409	0.491	0.223
	Precipitation, mean	90.918	92.418	0.500	0.222
	Sand and gravel	91.564	93.064	1.146	0.160
	Min annual monthly min temp	92.305	93.805	1.887	0.111
Land cover					
	Agriculture, 2011	**91.205**	**92.705**	**0.000**	**0.300**
	Agriculture, 1992	91.855	93.355	0.650	0.217
	Forest, 2011	92.192	93.692	0.987	0.183
	Open Water, 2011	92.586	94.086	1.381	0.150
	Wetland, 2011	92.593	94.093	1.388	0.150
Flow alteration					
	Flow altered, Aug	**89.434**	**90.934**	**0.000**	**0.450**
	Flow percent dif, Aug	90.079	91.579	0.646	0.326
	Dams, per drainage area	92.068	93.568	2.634	0.121
	Longest undammed flow path	92.376	93.876	2.943	0.103
Other urban measures					
	Gradient:length ratio, wgt 2.0	**91.600**	**93.100**	**0.000**	**0.168**
	Flow length, wgt 2.0	91.721	93.221	0.121	0.158
	Impervious, 2006 to 2011 dif	92.123	93.623	0.523	0.129
	Road crossings, total	92.220	93.720	0.621	0.123
	Road crossings, density	92.317	93.817	0.718	0.117
	Impervious, buffer, 10m-res	92.587	94.087	0.987	0.102
	Housing density	92.596	94.096	0.996	0.102
	Road density	92.598	94.098	0.998	0.102

Low band					
Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics					
	Min annual monthly min temp	**88.754**	**90.254**	**0.000**	**0.271**
	Drainage area	88.982	90.482	0.228	0.242
	Max annual monthly max temp	89.248	90.748	0.495	0.212
	Precipitation, mean	90.080	91.580	1.327	0.140
	Sand and gravel	90.155	91.655	1.401	0.135
Land cover					
	Forest, 2011	**89.352**	**90.852**	**0.000**	**0.322**
	Agriculture, 1992	90.054	91.554	0.702	0.227
	Open Water, 2011	90.797	92.297	1.445	0.156
	Wetland, 2011	90.915	92.415	1.563	0.147
	Agriculture, 2011	90.920	92.420	1.568	0.147
Flow alteration					
	Longest undammed flow path	**89.895**	**91.395**	**0.000**	**0.339**
	Flow percent dif, Aug	90.485	91.985	0.590	0.253
	Dams, per drainage area	90.904	92.404	1.009	0.205
	Flow altered, Aug	90.919	92.419	1.024	0.203
Other urban measures					
	Impervious, buffer, 10m-res	**88.262**	**89.762**	**0.000**	**0.247**
	Housing density	88.263	89.763	0.001	0.247
	Road crossings, total	89.661	91.161	1.399	0.123
	Gradient:length ratio, wgt 2.0	90.260	91.760	1.998	0.091
	Road crossings, density	90.409	91.909	2.147	0.085
	Flow length, wgt 2.0	90.694	92.194	2.432	0.073
	Road density	90.853	92.353	2.591	0.068
	Impervious, 2006 to 2011 dif	90.911	92.411	2.649	0.066

Appendix M.3. Macroinvertebrate flow traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Sand and gravel	**198.076**	**199.219**	**0.000**	**0.244**		**Min annual monthly min temp**	**87.651**	**90.317**	**0.000**	**0.571**		**Min annual monthly min temp**	**104.360**	**107.027**	**0.000**	**0.422**
	Max annual monthly max temp	198.396	199.539	0.320	0.208		Max annual monthly max temp	90.187	92.854	2.537	0.161		Sand and gravel	105.819	108.486	1.459	0.204
	Drainage area	198.594	199.736	0.517	0.188		Precipitation, mean	90.735	93.402	3.085	0.122		Max annual monthly max temp	106.772	109.439	2.412	0.126
	Precipitation, mean	198.607	199.750	0.531	0.187		Drainage area	91.718	94.385	4.067	0.075		Precipitation, mean	106.811	109.477	2.450	0.124
	Min annual monthly min temp	198.763	199.906	0.687	0.173		Sand and gravel	91.803	94.470	4.153	0.072		Drainage area	106.818	109.484	2.457	0.124
Land cover						Land cover						Land cover					
	Open Water, 2011	**192.227**	**193.370**	**0.000**	**0.851**		**Wetland, 2011**	**89.594**	**92.261**	**0.000**	**0.346**		**Open Water, 2011**	**101.686**	**104.352**	**0.000**	**0.614**
	Agriculture, 1992	197.918	199.061	5.691	0.049		Agriculture, 1992	90.261	92.928	0.666	0.248		Wetland, 2011	103.653	106.320	1.968	0.230
	Wetland, 2011	198.663	199.806	6.436	0.034		Forest, 2011	91.043	93.710	1.449	0.168		Agriculture, 1992	106.518	109.185	4.832	0.055
	Forest, 2011	198.740	199.883	6.513	0.033		Open Water, 2011	91.675	94.342	2.081	0.122		Forest, 2011	106.556	109.223	4.871	0.054
	Agriculture, 2011	198.758	199.901	6.532	0.032		Agriculture, 2011	91.765	94.432	2.171	0.117		Agriculture, 2011	106.780	109.446	5.094	0.048
Flow alteration						Flow alteration						Flow alteration					
	Dams, per drainage area	**194.531**	**195.674**	**0.000**	**0.612**		**Dams, per drainage area**	**91.530**	**94.197**	**0.000**	**0.268**		**Dams, per drainage area**	**103.144**	**105.811**	**0.000**	**0.579**
	Longest undammed flow path	197.140	198.283	2.609	0.166		Flow altered, Aug	91.602	94.269	0.072	0.259		Longest undammed flow path	105.373	108.040	2.229	0.190
	Flow percent dif, Aug	197.488	198.631	2.957	0.139		Longest undammed flow path	91.753	94.420	0.223	0.240		Flow percent dif, Aug	106.274	108.941	3.130	0.121
	Flow altered, Aug	198.532	199.675	4.001	0.083		Flow percent dif, Aug	91.809	94.475	0.279	0.233		Flow altered, Aug	106.479	109.146	3.335	0.109
Other urban measures						Other urban measures						Other urban measures					
	Impervious, 2006 to 2011 dif	**196.793**	**197.936**	**0.000**	**0.229**		**Housing density**	**90.147**	**92.814**	**0.000**	**0.212**		**Housing density**	**104.144**	**106.810**	**0.000**	**0.290**
	Gradient:length ratio, wgt 2.0	197.617	198.760	0.824	0.152		Road crossings, density	90.987	93.654	0.839	0.139		Impervious, 2006 to 2011 dif	105.252	107.919	1.109	0.167
	Flow length, wgt 2.0	197.703	198.846	0.911	0.145		Impervious, buffer, 10m-res	91.141	93.808	0.994	0.129		Flow length, wgt 2.0	106.154	108.820	2.010	0.106
	Housing density	198.486	199.628	1.693	0.098		Gradient:length ratio, wgt 2.0	91.273	93.940	1.126	0.121		Gradient:length ratio, wgt 2.0	106.155	108.821	2.011	0.106
	Road density	198.500	199.643	1.708	0.098		Road density	91.467	94.134	1.320	0.110		Road crossings, total	106.588	109.255	2.444	0.086
	Road crossings, density	198.523	199.666	1.731	0.097		Impervious, 2006 to 2011 dif	91.582	94.249	1.434	0.104		Impervious, buffer, 10m-res	106.634	109.301	2.490	0.084
	Road crossings, total	198.540	199.682	1.747	0.096		Flow length, wgt 2.0	91.772	94.439	1.625	0.094		Road crossings, density	106.639	109.305	2.495	0.083
	Impervious, buffer, 10m-res	198.769	199.912	1.977	0.085		Road crossings, total	91.839	94.505	1.691	0.091		Road density	106.779	109.445	2.635	0.078

Appendix M.4. Fish flow traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Min annual monthly min temp	**163.226**	**164.369**	**0.000**	**0.991**		**Min annual monthly min temp**	**89.184**	**91.851**	**0.000**	**0.781**		**Min annual monthly min temp**	**73.109**	**75.775**	**0.000**	**0.888**
	Max annual monthly max temp	173.697	174.840	10.471	0.005		Max annual monthly max temp	93.217	95.884	4.033	0.104		Max annual monthly max temp	78.595	81.261	5.486	0.057
	Sand and gravel	175.943	177.085	12.717	0.002		Sand and gravel	93.660	96.327	4.476	0.083		Drainage area	80.131	82.797	7.022	0.027
	Drainage area	176.404	177.547	13.178	0.001		Precipitation, mean	96.909	99.575	7.724	0.016		Precipitation, mean	81.256	83.923	8.147	0.015
	Precipitation, mean	177.481	178.624	14.255	0.001		Drainage area	97.044	99.711	7.860	0.015		Sand and gravel	81.492	84.159	8.383	0.013
Land cover						Land cover						Land cover					
	Wetland, 2011	**171.028**	**172.171**	**0.000**	**0.604**		**Wetland, 2011**	**91.342**	**94.008**	**0.000**	**0.584**		**Wetland, 2011**	**78.761**	**81.428**	**0.000**	**0.315**
	Forest, 2011	173.230	174.373	2.202	0.201		Agriculture, 1992	94.064	96.731	2.723	0.150		Forest, 2011	78.906	81.573	0.145	0.293
	Open Water, 2011	173.981	175.124	2.953	0.138		Forest, 2011	94.249	96.915	2.907	0.136		Open Water, 2011	79.781	82.448	1.020	0.189
	Agriculture, 1992	177.034	178.176	6.006	0.030		Open Water, 2011	95.117	97.784	3.775	0.088		Agriculture, 2011	80.528	83.195	1.767	0.130
	Agriculture, 2011	177.212	178.355	6.184	0.027		Agriculture, 2011	96.624	99.291	5.283	0.042		Agriculture, 1992	81.682	84.348	2.921	0.073
Flow alteration						Flow alteration						Flow alteration					
	Dams, per drainage area	**161.707**	**162.849**	**0.000**	**0.944**		**Dams, per drainage area**	**91.668**	**94.335**	**0.000**	**0.684**		**Flow percent dif, Aug**	**68.737**	**71.404**	**0.000**	**0.599**
	Flow percent dif, Aug	167.914	169.057	6.208	0.042		Flow percent dif, Aug	94.295	96.962	2.627	0.184		Flow altered, Aug	70.749	73.416	2.012	0.219
	Flow altered, Aug	170.196	171.339	8.489	0.014		Longest undammed flow path	96.199	98.866	4.531	0.071		Dams, per drainage area	71.121	73.788	2.385	0.182
	Longest undammed flow path	176.485	177.628	14.778	0.001		Flow altered, Aug	96.521	99.188	4.853	0.060		Longest undammed flow path	81.561	84.228	12.824	0.001
Other urban measures						Other urban measures						Other urban measures					
	Flow length, wgt 2.0	**165.461**	**166.604**	**0.000**	**0.573**		**Road crossings, density**	**91.877**	**94.543**	**0.000**	**0.409**		**Flow length, wgt 2.0**	**72.015**	**74.682**	**0.000**	**0.484**
	Impervious, buffer, 10m-res	166.215	167.358	0.754	0.393		Gradient:length ratio, wgt 2.0	94.134	96.801	2.258	0.132		Impervious, buffer, 10m-res	72.911	75.577	0.895	0.309
	Gradient:length ratio, wgt 2.0	172.000	173.143	6.539	0.022		Housing density	94.164	96.831	2.288	0.130		Gradient:length ratio, wgt 2.0	74.078	76.744	2.062	0.173
	Road crossings, total	174.945	176.088	9.484	0.005		Road density	95.114	97.781	3.237	0.081		Housing density	79.309	81.975	7.294	0.013
	Road crossings, density	176.340	177.483	10.879	0.002		Impervious, buffer, 10m-res	95.157	97.824	3.280	0.079		Road crossings, total	80.439	83.105	8.423	0.007
	Impervious, 2006 to 2011 dif	176.733	177.876	11.272	0.002		Impervious, 2006 to 2011 dif	95.261	97.928	3.385	0.075		Impervious, 2006 to 2011 dif	80.623	83.289	8.608	0.007
	Road density	176.915	178.057	11.453	0.002		Road crossings, total	95.654	98.320	3.777	0.062		Road crossings, density	81.706	84.373	9.691	0.004
	Housing density	177.480	178.623	12.019	0.001		Flow length, wgt 2.0	96.969	99.636	5.092	0.032		Road density	81.708	84.374	9.692	0.004

Appendix M.5. Macroinvertebrate thermal traits models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Drainage area	**174.856**	**175.999**	**0.000**	**0.457**		**Sand and gravel**	**85.056**	**87.722**	**0.000**	**0.701**		**Drainage area**	**90.568**	**93.234**	**0.000**	**0.436**
	Sand and gravel	175.651	176.794	0.795	0.307		Drainage area	88.008	90.675	2.952	0.160		Precipitation, mean	92.610	95.277	2.043	0.157
	Min annual monthly min temp	177.934	179.077	3.078	0.098		Min annual monthly min temp	90.181	92.848	5.125	0.054		Min annual monthly min temp	92.833	95.500	2.266	0.140
	Precipitation, mean	178.604	179.746	3.747	0.070		Max annual monthly max temp	90.466	93.133	5.410	0.047		Sand and gravel	92.856	95.522	2.288	0.139
	Max annual monthly max temp	178.652	179.795	3.796	0.068		Precipitation, mean	90.926	93.593	5.871	0.037		Max annual monthly max temp	93.016	95.683	2.449	0.128
Land cover						Land cover						Land cover					
	Open Water, 2011	**166.502**	**167.644**	**0.000**	**0.983**		**Open Water, 2011**	**84.740**	**87.407**	**0.000**	**0.578**		**Open Water, 2011**	**85.666**	**88.333**	**0.000**	**0.907**
	Wetland, 2011	175.859	177.002	9.357	0.009		Wetland, 2011	86.394	89.061	1.654	0.253		Wetland, 2011	92.656	95.323	6.990	0.028
	Agriculture, 1992	178.030	179.172	11.528	0.003		Forest, 2011	88.061	90.728	3.321	0.110		Forest, 2011	93.058	95.724	7.391	0.023
	Agriculture, 2011	178.434	179.577	11.933	0.003		Agriculture, 1992	90.529	93.196	5.789	0.032		Agriculture, 1992	93.136	95.803	7.470	0.022
	Forest, 2011	178.495	179.638	11.993	0.002		Agriculture, 2011	90.865	93.531	6.124	0.027		Agriculture, 2011	93.163	95.829	7.497	0.021
Flow alteration						Flow alteration						Flow alteration					
	Dams, per drainage area	**170.906**	**172.049**	**0.000**	**0.921**		**Dams, per drainage area**	**82.421**	**85.088**	**0.000**	**0.924**		**Dams, per drainage area**	**90.740**	**93.407**	**0.000**	**0.423**
	Longest undammed flow path	177.557	178.700	6.651	0.033		Flow percent dif, Aug	88.292	90.958	5.870	0.049		Flow altered, Aug	91.947	94.614	1.207	0.231
	Flow altered, Aug	177.998	179.141	7.092	0.027		Longest undammed flow path	90.779	93.445	8.357	0.014		Longest undammed flow path	92.206	94.872	1.465	0.203
	Flow percent dif, Aug	178.646	179.789	7.740	0.019		Flow altered, Aug	91.023	93.690	8.601	0.013		Flow percent dif, Aug	92.917	95.584	2.177	0.142
Other urban measures						Other urban measures						Other urban measures					
	Road crossings, total	**170.385**	**171.527**	**0.000**	**0.836**		**Road crossings, total**	**82.507**	**85.173**	**0.000**	**0.714**		**Road density**	**90.811**	**93.478**	**0.000**	**0.219**
	Road crossings, density	176.787	177.930	6.403	0.034		Road density	86.171	88.838	3.665	0.114		Road crossings, total	91.039	93.706	0.228	0.196
	Impervious, 2006 to 2011 dif	176.904	178.047	6.520	0.032		Housing density	87.369	90.036	4.863	0.063		Impervious, 2006 to 2011 dif	91.244	93.911	0.433	0.176
	Impervious, buffer, 10m-res	177.279	178.422	6.894	0.027		Road crossings, density	88.530	91.197	6.024	0.035		Impervious, buffer, 10m-res	91.732	94.399	0.921	0.138
	Housing density	177.707	178.850	7.323	0.021		Flow length, wgt 2.0	89.347	92.014	6.841	0.023		Flow length, wgt 2.0	93.142	95.809	2.331	0.068
	Road density	177.853	178.995	7.468	0.020		Gradient:length ratio, wgt 2.0	89.603	92.269	7.096	0.021		Housing density	93.146	95.813	2.335	0.068
	Flow length, wgt 2.0	178.414	179.557	8.030	0.015		Impervious, 2006 to 2011 dif	89.639	92.306	7.133	0.020		Gradient:length ratio, wgt 2.0	93.180	95.846	2.368	0.067
	Gradient:length ratio, wgt 2.0	178.430	179.573	8.045	0.015		Impervious, buffer, 10m-res	91.004	93.670	8.497	0.010		Road crossings, density	93.181	95.848	2.370	0.067

Appendix M.6. Fish thermal traits models with impervious cover and one additional predictor. Model selection was performed with Akaike’s Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Min annual monthly min temp	**149.030**	**150.173**	**0.000**	**0.969**		**Min annual monthly min temp**	**93.813**	**96.480**	**0.000**	**0.977**		**Min annual monthly min temp**	**56.874**	**59.540**	**0.000**	**0.476**
	Precipitation, mean	157.537	158.679	8.506	0.014		Precipitation, mean	103.268	105.935	9.455	0.009		Max annual monthly max temp	58.714	61.380	1.840	0.190
	Max annual monthly max temp	158.912	160.055	9.882	0.007		Max annual monthly max temp	103.566	106.233	9.753	0.007		Drainage area	59.295	61.962	2.421	0.142
	Drainage area	159.164	160.306	10.133	0.006		Sand and gravel	105.032	107.699	11.219	0.004		Precipitation, mean	59.956	62.622	3.082	0.102
	Sand and gravel	159.877	161.020	10.847	0.004		Drainage area	105.419	108.086	11.607	0.003		Sand and gravel	60.175	62.842	3.301	0.091
Land cover						Land cover						Land cover					
	Wetland, 2011	**156.702**	**157.845**	**0.000**	**0.415**		**Forest, 2011**	**96.346**	**99.013**	**0.000**	**0.817**		**Agriculture, 1992**	**58.246**	**60.913**	**0.000**	**0.359**
	Agriculture, 1992	157.410	158.553	0.708	0.291		Wetland, 2011	99.803	102.470	3.457	0.145		Agriculture, 2011	59.633	62.300	1.387	0.179
	Forest, 2011	159.339	160.482	2.637	0.111		Open Water, 2011	104.315	106.982	7.970	0.015		Forest, 2011	59.733	62.399	1.486	0.171
	Open Water, 2011	159.490	160.633	2.788	0.103		Agriculture, 2011	104.366	107.033	8.020	0.015		Wetland, 2011	59.994	62.660	1.747	0.150
	Agriculture, 2011	160.009	161.152	3.307	0.079		Agriculture, 1992	105.608	108.275	9.262	0.008		Open Water, 2011	60.111	62.777	1.864	0.141
Flow alteration						Flow alteration						Flow alteration					
	Dams, per drainage area	**157.424**	**158.567**	**0.000**	**0.382**		**Flow percent dif, Aug**	**101.555**	**104.222**	**0.000**	**0.559**		**Longest undammed flow path**	**59.008**	**61.675**	**0.000**	**0.335**
	Longest undammed flow path	158.201	159.344	0.777	0.259		Dams, per drainage area	102.973	105.640	1.418	0.275		Dams, per drainage area	59.374	62.040	0.366	0.279
	Flow percent dif, Aug	158.403	159.546	0.979	0.234		Longest undammed flow path	105.244	107.911	3.689	0.088		Flow percent dif, Aug	60.044	62.711	1.037	0.200
	Flow altered, Aug	159.656	160.798	2.231	0.125		Flow altered, Aug	105.525	108.191	3.969	0.077		Flow altered, Aug	60.182	62.848	1.174	0.186
Other urban measures						Other urban measures						Other urban measures					
	Impervious, buffer, 10m-res	**156.609**	**157.752**	**0.000**	**0.403**		**Gradient:length ratio, wgt 2.0**	**102.283**	**104.949**	**0.000**	**0.312**		**Impervious, buffer, 10m-res**	**55.769**	**58.436**	**0.000**	**0.500**
	Road crossings, total	158.877	160.020	2.268	0.130		Impervious, 2006 to 2011 dif	102.683	105.350	0.400	0.256		Road crossings, density	58.706	61.373	2.937	0.115
	Flow length, wgt 2.0	159.699	160.842	3.090	0.086		Housing density	104.443	107.109	2.160	0.106		Housing density	59.091	61.758	3.322	0.095
	Road density	159.867	161.010	3.258	0.079		Road crossings, total	104.848	107.514	2.565	0.087		Gradient:length ratio, wgt 2.0	59.995	62.662	4.226	0.060
	Gradient:length ratio, wgt 2.0	159.876	161.018	3.267	0.079		Flow length, wgt 2.0	105.330	107.997	3.048	0.068		Road crossings, total	60.056	62.722	4.286	0.059
	Road crossings, density	159.941	161.083	3.332	0.076		Impervious, buffer, 10m-res	105.527	108.194	3.244	0.062		Impervious, 2006 to 2011 dif	60.091	62.758	4.322	0.058
	Impervious, 2006 to 2011 dif	159.991	161.134	3.382	0.074		Road density	105.759	108.426	3.476	0.055		Road density	60.097	62.764	4.328	0.057
	Housing density	160.034	161.177	3.425	0.073		Road crossings, density	105.782	108.449	3.499	0.054		Flow length, wgt 2.0	60.171	62.838	4.402	0.055

Appendix M.7. Macroinvertebrate tolerance index models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Min annual monthly min temp	**104.431**	**105.574**	**0.000**	**0.824**		**Min annual monthly min temp**	**43.858**	**46.525**	**0.000**	**0.984**		**Precipitation, mean**	**53.891**	**56.557**	**0.000**	**0.542**
	Sand and gravel	109.044	110.187	4.613	0.082		Max annual monthly max temp	52.428	55.095	8.570	0.014		Sand and gravel	55.130	57.797	1.240	0.291
	Max annual monthly max temp	109.256	110.399	4.825	0.074		Sand and gravel	57.465	60.131	13.607	0.001		Drainage area	58.210	60.877	4.320	0.062
	Precipitation, mean	112.980	114.123	8.549	0.011		Precipitation, mean	58.928	61.595	15.070	0.001		Min annual monthly min temp	58.419	61.086	4.529	0.056
	Drainage area	113.560	114.702	9.129	0.009		Drainage area	59.287	61.954	15.429	0.000		Max annual monthly max temp	58.729	61.396	4.839	0.048
Land cover						Land cover						Land cover					
	Forest, 2011	**107.975**	**109.118**	**0.000**	**0.500**		**Wetland, 2011**	**56.012**	**58.678**	**0.000**	**0.403**		**Forest, 2011**	**55.477**	**58.144**	**0.000**	**0.389**
	Wetland, 2011	109.075	110.218	1.100	0.288		Forest, 2011	56.562	59.229	0.551	0.306		Agriculture, 2011	56.153	58.819	0.676	0.277
	Agriculture, 2011	110.466	111.609	2.491	0.144		Agriculture, 1992	58.543	61.209	2.531	0.114		Agriculture, 1992	57.666	60.333	2.189	0.130
	Open Water, 2011	113.313	114.456	5.338	0.035		Agriculture, 2011	58.958	61.625	2.946	0.092		Wetland, 2011	57.826	60.493	2.349	0.120
	Agriculture, 1992	113.381	114.524	5.406	0.033		Open Water, 2011	59.117	61.784	3.105	0.085		Open Water, 2011	58.543	61.210	3.066	0.084
Flow alteration						Flow alteration						Flow alteration					
	Longest undammed flow path	**112.374**	**113.517**	**0.000**	**0.366**		**Flow percent dif, Aug**	**58.561**	**61.228**	**0.000**	**0.312**		**Longest undammed flow path**	**58.027**	**60.694**	**0.000**	**0.321**
	Dams, per drainage area	113.357	114.499	0.983	0.224		Dams, per drainage area	58.642	61.309	0.081	0.299		Flow percent dif, Aug	58.728	61.395	0.701	0.226
	Flow percent dif, Aug	113.443	114.586	1.069	0.214		Longest undammed flow path	59.433	62.100	0.872	0.202		Dams, per drainage area	58.730	61.396	0.703	0.226
	Flow altered, Aug	113.616	114.759	1.242	0.196		Flow altered, Aug	59.580	62.247	1.019	0.187		Flow altered, Aug	58.730	61.396	0.703	0.226
Other urban measures						Other urban measures						Other urban measures					
	Impervious, buffer, 10m-res	**111.693**	**112.836**	**0.000**	**0.238**		**Gradient:length ratio, wgt 2.0**	**51.020**	**53.687**	**0.000**	**0.873**		**Impervious, buffer, 10m-res**	**56.221**	**58.888**	**0.000**	**0.260**
	Housing density	112.594	113.737	0.902	0.152		Impervious, 2006 to 2011 dif	57.517	60.183	6.497	0.034		Impervious, 2006 to 2011 dif	56.578	59.245	0.357	0.218
	Impervious, 2006 to 2011 dif	112.665	113.808	0.972	0.147		Housing density	58.238	60.905	7.218	0.024		Gradient:length ratio, wgt 2.0	58.249	60.916	2.028	0.094
	Gradient:length ratio, wgt 2.0	113.408	114.551	1.715	0.101		Flow length, wgt 2.0	58.968	61.634	7.948	0.016		Road crossings, total	58.289	60.956	2.068	0.093
	Flow length, wgt 2.0	113.585	114.727	1.892	0.093		Road crossings, total	59.206	61.873	8.186	0.015		Flow length, wgt 2.0	58.315	60.981	2.093	0.091
	Road crossings, density	113.644	114.787	1.951	0.090		Road crossings, density	59.323	61.990	8.303	0.014		Road density	58.340	61.007	2.119	0.090
	Road density	113.647	114.790	1.954	0.090		Impervious, buffer, 10m-res	59.517	62.184	8.497	0.012		Road crossings, density	58.637	61.303	2.415	0.078
	Road crossings, total	113.647	114.790	1.954	0.090		Road density	59.580	62.247	8.560	0.012		Housing density	58.681	61.347	2.459	0.076

Appendix M.8. Fish, intolerant models with impervious cover and one additional predictor. Model selection was performed with Akaike's Information Criterion (AIC), corrected for sample size and number of parameters (AICc; Burnham et al. 2011); model weights (*w*) were calculated relative to other models tested. Predictors with the lowest AICc (ΔAICc = 0) were used in the global model; predictors are indicated in bold. Impervious bands were tested together (both bands, *n* = 40) and separately (very-low band, 1–4%, *n* = 20; low band, 7–10%, *n* = 20).

Both bands						Very-low band						Low band					
Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w	Group	Predictor	AIC	AICc	ΔAICc	w
Natural characteristics						Natural characteristics						Natural characteristics					
	Min annual monthly min temp	**129.614**	**130.757**	**0.000**	**0.384**		**Precipitation, mean**	**79.144**	**81.811**	**0.000**	**0.362**		**Max annual monthly max temp**	**52.360**	**55.027**	**0.000**	**0.358**
	Drainage area	130.115	131.258	0.501	0.298		Drainage area	79.624	82.291	0.480	0.285		Drainage area	52.893	55.560	0.533	0.274
	Precipitation, mean	131.535	132.678	1.921	0.147		Min annual monthly min temp	80.686	83.353	1.542	0.167		Min annual monthly min temp	54.231	56.898	1.871	0.141
	Max annual monthly max temp	132.525	133.668	2.911	0.089		Sand and gravel	81.597	84.264	2.453	0.106		Sand and gravel	54.628	57.295	2.268	0.115
	Sand and gravel	132.706	133.849	3.092	0.082		Max annual monthly max temp	82.158	84.825	3.014	0.080		Precipitation, mean	54.693	57.359	2.332	0.112
Land cover						Land cover						Land cover					
	Open Water, 2011	**129.391**	**130.534**	**0.000**	**0.423**		**Forest, 2011**	**73.703**	**76.370**	**0.000**	**0.714**		**Wetland, 2011**	**53.173**	**55.840**	**0.000**	**0.301**
	Forest, 2011	130.903	132.046	1.512	0.199		Wetland, 2011	76.086	78.752	2.383	0.217		Open Water, 2011	53.915	56.582	0.742	0.208
	Wetland, 2011	131.303	132.446	1.912	0.163		Open Water, 2011	79.380	82.047	5.677	0.042		Forest, 2011	53.927	56.593	0.754	0.207
	Agriculture, 2011	132.092	133.235	2.701	0.110		Agriculture, 2011	81.638	84.305	7.935	0.014		Agriculture, 1992	54.345	57.011	1.172	0.168
	Agriculture, 1992	132.149	133.292	2.758	0.106		Agriculture, 1992	81.663	84.329	7.960	0.013		Agriculture, 2011	55.074	57.741	1.901	0.116
Flow alteration						Flow alteration						Flow alteration					
	Dams, per drainage area	**129.838**	**130.981**	**0.000**	**0.470**		**Dams, per drainage area**	**80.030**	**82.697**	**0.000**	**0.423**		**Flow altered, Aug**	**52.977**	**55.643**	**0.000**	**0.380**
	Flow altered, Aug	130.832	131.975	0.994	0.286		Flow altered, Aug	80.551	83.218	0.521	0.326		Dams, per drainage area	53.791	56.457	0.814	0.253
	Longest undammed flow path	132.470	133.613	2.633	0.126		Longest undammed flow path	82.433	85.100	2.403	0.127		Longest undammed flow path	54.184	56.851	1.207	0.208
	Flow percent dif, Aug	132.585	133.727	2.747	0.119		Flow percent dif, Aug	82.481	85.148	2.451	0.124		Flow percent dif, Aug	54.729	57.395	1.752	0.158
Other urban measures						Other urban measures						Other urban measures					
	Road crossings, total	**128.263**	**129.406**	**0.000**	**0.407**		**Flow length, wgt 2.0**	**78.286**	**80.952**	**0.000**	**0.403**		**Housing density**	**50.384**	**53.050**	**0.000**	**0.488**
	Road crossings, density	129.668	130.811	1.405	0.201		Road crossings, total	80.111	82.777	1.825	0.162		Road crossings, total	52.499	55.165	2.115	0.169
	Flow length, wgt 2.0	130.975	132.118	2.712	0.105		Road density	80.844	83.511	2.558	0.112		Flow length, wgt 2.0	54.338	57.004	3.954	0.068
	Road density	131.538	132.681	3.275	0.079		Road crossings, density	81.387	84.054	3.101	0.086		Road density	54.385	57.052	4.001	0.066
	Impervious, buffer, 10m-res	132.089	133.232	3.826	0.060		Impervious, buffer, 10m-res	81.658	84.325	3.373	0.075		Road crossings, density	54.587	57.254	4.203	0.060
	Housing density	132.224	133.367	3.961	0.056		Gradient:length ratio, wgt 2.0	82.173	84.840	3.887	0.058		Impervious, 2006 to 2011 dif	54.823	57.490	4.439	0.053
	Gradient:length ratio, wgt 2.0	132.606	133.749	4.343	0.046		Housing density	82.280	84.947	3.995	0.055		Impervious, buffer, 10m-res	54.975	57.641	4.591	0.049
	Impervious, 2006 to 2011 dif	132.630	133.772	4.366	0.046		Impervious, 2006 to 2011 dif	82.484	85.151	4.198	0.049		Gradient:length ratio, wgt 2.0	55.058	57.725	4.674	0.047

APPENDIX N:

EQUALLY PLAUSIBLE MODELS FROM ALL-SUBSETS GLMS AND GLMMS WITH WATERSHED-SCALE PREDICTORS

Appendix N. Equally plausible models from all subsets modeling. All subsets of GLMs and GLMMs were run with impervious and the top four predictors from each predictor category for each biotic response variable and for each impervious band. Equally plausible models are those within < 2 ΔAICc units. The variance explained by each model was calculated with R^2 for macroinvertebrate richness and macroinvertebrate tolerance (GLM with Gaussian distribution); pseudo-R^2 for fish richness (GLM with Poisson distribution); and conditional-R^2 for relative abundances of macroinvertebrate flow traits, fluvial fish, coldwater macroinvertebrates, coldwater fishes, and intolerant fishes (GLMM with binomial distribution).

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Richness									
Macroinvertebrate richness									
	Both bands								
		1	IC.2011 + Agriculture.1992 + pctImp.Buffer.10m	40	4	274.770	0.000	0.114	0.238
		2	IC.2011 + Agriculture.1992 + AugAlt.cms	40	4	275.099	0.329	0.097	0.232
		3	IC.2011 + Agriculture.1992	40	3	275.396	0.626	0.083	0.177
		4	IC.2011 + pctImp.Buffer.10m	40	3	275.591	0.821	0.075	0.173
		5	IC.2011 + Agriculture.1992 + AugAlt.cms + pctImp.Buffer.10m	40	5	275.942	1.172	0.063	0.266
		6	IC.2011 + SandGravel_pct + Agriculture.1992 + pctImp.Buffer.10m	40	5	276.278	1.508	0.054	0.259
		7	IC.2011 + SandGravel_pct + pctImp.Buffer.10m	40	4	276.406	1.636	0.050	0.207
		8	IC.2011 + SandGravel_pct + Agriculture.1992	40	4	276.466	1.696	0.049	0.205
	Low band								
		1	Agriculture.1992	20	2	274.924	0.000	0.207	0.183
		2	IC.2011 + Agriculture.1992	20	3	275.773	0.849	0.135	0.293
		3	IC.2011	20	2	276.527	1.603	0.093	0.020
	High band								
		1	SandGravel_pct	20	2	278.283	0.000	0.210	0.012
		2	OpenWater.2011	20	2	279.987	1.704	0.089	0.142
Fish richness									
	Both bands								
		1	IC.2011 + Area.sqkm	40	3	177.102	0.000	0.139	0.223
		2	IC.2011 + Area.sqkm + Forest.2011	40	4	177.467	0.365	0.116	0.279
		3	IC.2011 + Forest.2011	40	3	178.179	1.077	0.081	0.195
		4	IC.2011	40	2	178.381	1.279	0.074	0.128
		5	IC.2011 + RoadCrossings	40	3	178.904	1.802	0.057	0.176
	Low band								
		1	AugAlt.cms	20	2	88.370	0.000	0.163	0.224
		2	TMax.maxC	20	2	89.383	1.013	0.098	0.148
		3	Agriculture.2011 + AugAlt.cms	20	3	89.753	1.383	0.082	0.330
		4	Agriculture.2011	20	2	90.028	1.658	0.071	0.099
		5	AugAlt.cms + GLR2	20	3	90.316	1.946	0.062	0.288
		6	GLR2	20	2	90.351	1.981	0.060	0.075
	High band								
		1	IC.2011	20	2	89.627	0.000	0.096	0.184
		2	IC.2011 + pctImp.Buffer.10m	20	3	89.762	0.135	0.090	0.309
		3	IC.2011 + TMin.minC	20	3	90.254	0.627	0.071	0.286
		4	UnDamLFPDistTOT_km	20	2	90.374	0.747	0.066	0.150
		5	UnDamLFPDistTOT_km + pctImp.Buffer.10m	20	3	90.630	1.003	0.058	0.268
		6	IC.2011 + Forest.2011 + pctImp.Buffer.10m	20	3	90.640	1.013	0.058	0.416
		7	TMin.minC + UnDamLFPDistTOT_km	20	3	90.812	1.185	0.053	0.260
		8	IC.2011 + Forest.2011	20	3	90.852	1.225	0.052	0.258
		9	IC.2011 + UnDamLFPDistTOT_km + pctImp.Buffer.10m	20	4	91.363	1.736	0.040	0.382
		10	IC.2011 + UnDamLFPDistTOT_km	20	3	91.395	1.768	0.040	0.232

Appendix N, continued

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Flow traits									
Macroinvertebrate flow traits									
	Both bands								
		1	OpenWater.2011 + IC.06.11.dif + (1|UniqueID)	40	4	190.198	0.000	0.185	0.064
		2	OpenWater.2011 + (1|UniqueID)	40	3	190.948	0.750	0.127	0.045
		3	IC.2011 + OpenWater.2011 + IC.06.11.dif + (1|UniqueID)	40	5	191.611	1.412	0.092	0.070
		4	OpenWater.2011 + DamDen.sqkm + IC.06.11.dif + (1|UniqueID)	40	5	192.143	1.945	0.070	0.067
	Low band								
		1	TMin.minC + (1|UniqueID)	20	3	87.554	0.000	0.260	0.037
	High band								
		1	OpenWater.2011 + (1|UniqueID)	20	3	101.689	0.000	0.133	0.100
		2	OpenWater.2011 + HousDen.sqkm + (1|UniqueID)	20	4	101.845	0.156	0.123	0.140
		3	TMin.minC + OpenWater.2011 + (1|UniqueID)	20	4	102.147	0.459	0.106	0.136
		4	TMin.minC + OpenWater.2011 + HousDen.sqkm + (1|UniqueID)	20	5	102.240	0.551	0.101	0.176
		5	DamDen.sqkm + (1|UniqueID)	20	3	103.204	1.516	0.063	0.076
		6	DamDen.sqkm + HousDen.sqkm + (1|UniqueID)	20	4	103.283	1.594	0.060	0.120
Fish flow traits									
	Both bands								
		1	IC.2011 + TMin.minC + DamDen.sqkm + FL2 + (1|UniqueID)	40	6	152.040	0.000	0.411	0.530
		2	IC.2011 + TMin.minC + Wetland.2011 + DamDen.sqkm + FL2 + (1|UniqueID)	40	7	153.402	1.363	0.208	0.553
	Low band								
		1	TMin.minC + DamDen.sqkm + (1|UniqueID)	20	4	86.486	0.000	0.235	0.334
		2	TMin.minC + RoadCrossings.sqkm + (1|UniqueID)	20	4	87.071	0.584	0.176	0.320
		3	TMin.minC + DamDen.sqkm + RoadCrossings.sqkm + (1|UniqueID)	20	5	87.894	1.407	0.116	0.368
	High band								
		1	TMin.minC + AugPctDif + (1|UniqueID)	20	4	67.371	0.000	0.295	0.819
		2	IC.2011 + TMin.minC + AugPctDif + (1|UniqueID)	20	5	67.944	0.573	0.222	0.829

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Thermal traits									
Macroinvertebrate thermal traits									
	Both bands								
		1	IC.2011 + OpenWater.2011 + RoadCrossings + (1|UniqueID)	40	5	165.288	0.000	0.188	0.106
		2	OpenWater.2011 + RoadCrossings + (1|UniqueID)	40	4	165.467	0.179	0.172	0.095
		3	Area.sqkm + OpenWater.2011 + RoadCrossings + (1|UniqueID)	40	5	166.234	0.946	0.117	0.103
	Low band								
		1	IC.2011 + DamDen.sqkm + RoadCrossings + (1|UniqueID)	20	5	84.297	0.000	0.161	0.121
		2	IC.2011 + DamDen.sqkm + (1|UniqueID)	20	4	85.088	0.791	0.108	0.103
		3	IC.2011 + RoadCrossings + (1|UniqueID)	20	4	85.173	0.877	0.104	0.095
		4	RoadCrossings + (1|UniqueID)	20	3	85.975	1.679	0.069	0.070
	High band								
		1	OpenWater.2011 + RoadDen.km.sqkm + (1|UniqueID)	20	4	81.524	0.000	0.405	0.144
		2	Area.sqkm + OpenWater.2011 + RoadDen.km.sqkm + (1|UniqueID)	20	5	83.014	1.490	0.192	0.154
Fish thermal traits									
	Both bands								
		1	TMin.minC + (1|UniqueID)	40	3	148.496	0.000	0.291	0.296
		2	IC.2011 + TMin.minC + (1|UniqueID)	40	4	150.173	1.677	0.126	0.297
	Low band								
		1	IC.2011 + Forest.2011 + AugPctDif + GLR2 + (1|UniqueID)	20	6	95.035	0.000	0.178	0.602
		2	IC.2011 + Forest.2011 + GLR2 + (1|UniqueID)	20	5	95.552	0.517	0.137	0.565
		3	TMin.minC + (1|UniqueID)	20	3	96.161	1.127	0.101	0.320
		4	IC.2011 + TMin.minC + (1|UniqueID)	20	4	96.480	1.445	0.086	0.421
	High band								
		1	IC.2011 + pctImp.Buffer.10m + (1|UniqueID)	20	4	58.436	0.000	0.092	0.299
		2	UnDamLFPDistTOT_km + pctImp.Buffer.10m + (1|UniqueID)	20	4	58.651	0.215	0.083	0.323
		3	Agriculture.1992 + UnDamLFPDistTOT_km + pctImp.Buffer.10m + (1|UniqueID)	20	5	59.146	0.710	0.065	0.398
		4	IC.2011 + UnDamLFPDistTOT_km + pctImp.Buffer.10m + (1|UniqueID)	20	5	59.182	0.746	0.063	0.435
		5	TMin.minC + (1|UniqueID)	20	3	59.461	1.025	0.055	0.111
		6	IC.2011 + TMin.minC + (1|UniqueID)	20	4	59.540	1.104	0.053	0.222
		7	IC.2011 + (1|UniqueID)	20	3	59.682	1.246	0.049	0.116
		8	UnDamLFPDistTOT_km + (1|UniqueID)	20	3	59.787	1.351	0.047	0.145
		9	pctImp.Buffer.10m + (1|UniqueID)	20	3	59.804	1.368	0.046	0.111
		10	Agriculture.1992 + UnDamLFPDistTOT_km + (1|UniqueID)	20	4	59.850	1.415	0.045	0.296
		11	Agriculture.1992 + (1|UniqueID)	20	3	59.928	1.492	0.044	0.092
		12	TMin.minC + UnDamLFPDistTOT_km + (1|UniqueID)	20	4	60.035	1.599	0.041	0.049
		13	IC.2011 + Agriculture.1992 + pctImp.Buffer.10m + (1|UniqueID)	20	5	60.193	1.757	0.038	0.144

Appendix N, continued

Response	Band	Rank	Variables	n	df	AICc	ΔAICc	w	R2
Tolerance									
Macroinvertebrate tolerance index									
	Both bands								
		1	TMin.minC + UnDamLFPDistTOT_km	40	3	102.139	0.000	0.185	0.310
		2	TMin.minC	40	2	102.834	0.695	0.131	0.255
		3	TMin.minC + Forest.2011 + UnDamLFPDistTOT_km	40	4	103.769	1.630	0.082	0.324
		4	TMin.minC + Forest.2011	40	3	103.805	1.666	0.080	0.280
	Low band								
		1	TMin.minC	20	2	44.274	0.000	0.219	0.577
		2	TMin.minC + GLR2	20	3	44.919	0.645	0.159	0.620
		3	IC.2011 + TMin.minC + GLR2	20	4	45.254	0.980	0.134	0.670
		4	IC.2011 + TMin.minC	20	3	45.358	1.084	0.127	0.611
	High band								
		1	IC.2011 + Precip.mean.mm	20	3	55.391	0.000	0.100	0.279
		2	Forest.2011	20	2	55.623	0.232	0.089	0.161
		3	IC.2011 + Precip.mean.mm + pctImp.Buffer.10m	20	4	55.771	0.380	0.083	0.373
		4	Forest.2011 + UnDamLFPDistTOT_km	20	3	55.957	0.566	0.075	0.258
		5	Precip.mean.mm	20	2	56.853	1.462	0.048	0.108
		6	IC.2011 + Forest.2011	20	3	56.977	1.586	0.045	0.219
		7	Forest.2011 + UnDamLFPDistTOT_km + pctImp.Buffer.10m	20	4	57.334	1.943	0.038	0.322
Fish intolerance									
	Both bands								
		1	TMin.minC + OpenWater.2011 + RoadCrossings + (1|UniqueID)	40	5	124.722	0.000	0.131	0.367
		2	TMin.minC + RoadCrossings + (1|UniqueID)	40	4	124.892	0.170	0.120	0.263
		3	TMin.minC + DamDen.sqkm + RoadCrossings + (1|UniqueID)	40	5	124.945	0.223	0.117	0.301
		4	TMin.minC + DamDen.sqkm + (1|UniqueID)	40	4	125.125	0.403	0.107	0.255
		5	TMin.minC + OpenWater.2011 + (1|UniqueID)	40	4	125.561	0.839	0.086	0.332
		6	TMin.minC + OpenWater.2011 + DamDen.sqkm + (1|UniqueID)	40	5	126.248	1.525	0.061	0.341
		7	TMin.minC + OpenWater.2011 + DamDen.sqkm + RoadCrossings + (1|UniqueID)	40	6	126.713	1.991	0.048	0.360
	Low band								
		1	Forest.2011 + FL2 + (1|UniqueID)	20	4	71.520	0.000	0.297	0.549
		2	Forest.2011 + DamDen.sqkm + FL2 + (1|UniqueID)	20	5	72.818	1.299	0.155	0.606
	High band								
		1	HousDen.sqkm + (1|UniqueID)	20	3	49.961	0.000	0.222	0.200
		2	TMax.maxC + HousDen.sqkm + (1|UniqueID)	20	4	51.386	1.424	0.109	0.257
		3	AugAlt.cms + HousDen.sqkm + (1|UniqueID)	20	4	51.812	1.851	0.088	0.264

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