November 2016

Effects of Urbanization on Aquatic Life of Maine Streams

Narraguagus River

Thomas J. Danielson, Ph.D.
Leonidas Tsomides
Douglas Suitor
Jeanne L. DiFranco
Beth Connors

MAINE DEPARTMENT OF ENVIRONMENTAL PROTECTION
17 State House Station | Augusta, Maine 04333-0017
http://www.maine.gov/dep/water/monitoring/biomonitoring/

Executive Summary

Maine is fortunate to have many high quality streams with good water quality. To keep our streams healthy, Maine has water quality standards with four levels of water quality goals: Class AA, Class A, Class B, and Class C. Each stream in the state has been assigned to one of these four classes by the State Legislature. The Department of Environmental Protection (DEP) collects and analyzes samples of macroinvertebrates and algae from streams to determine if a stream attains biological criteria of its designated class (AA/A, B, or C).

Development of urban and residential areas has damaged some of Maine's streams to the point that they no longer support healthy communities of aquatic life or attain water quality standards. This study focuses on one aspect of urbanization, impervious cover (IC), and its relationship with the condition of aquatic communities in streams. IC includes hard surfaces, such as roofs, pavement, cement, and compacted soil that prevent infiltration of water into the ground. Streams with a lot of IC in their watersheds typically suffer from a variety of stressors, such as stream bank erosion, channel alteration, habitat degradation, warmer water, polluted water, harmful chemicals, and loss of riparian vegetation. The resulting conditions are unfavorable to aquatic organisms that require cold, clean water and high quality habitat. If a stream does not attain biological criteria of its designated class, then restoration is needed to improve water quality.

DEP determined the % IC in 140 watersheds upstream of sample locations and examined relationships with the condition of aquatic communities collected at the sample locations. In general, streams become vulnerable to no longer attaining Class AA/A biological criteria when % IC in upstream watersheds is in the range of 1-3% IC. The risk of not attaining Class B biological criteria increases in the range of 3-6% IC. Finally, the transition from low risk to high risk of attaining Class C criteria is in the range of 10-15% IC. Various factors may make a stream more or less vulnerable to negative impacts from IC. Some streams may maintain healthy aquatic communities at greater % IC than the ranges shown above because of stream or watershed factors that mitigate negative impacts of development. In contrast, other streams have stream or watershed characteristics that make them more vulnerable and less resilient to development. The location of IC matters. In general, development and IC close to the stream or its riparian corridor will have greater impact than development further away. Watershed management and restoration plans must account for other stream and watershed characteristics to successfully maintain or restore stream condition.

The purpose of this study is to provide information to improve successful restoration of urban streams and protection of streams in urbanizing areas. DEP previously developed IC Total Maximum Daily Load (TMDL) targets for some urban streams. The IC ranges in this study are lower than the IC targets in the TMDLs because of more robust analysis and transition from IC spatial data with 5 m resolution to spatial data with 1 m resolution. The 5 m data overestimated % IC in watersheds with more development when compared to the newer 1 m data. It might not be necessary to revise the TMDLs because the measurement of TMDL success is restoring water quality and aquatic life communities, not reaching a specific IC target.

Streams can support more IC in their watersheds if best management practices are used to mitigate development and steps are taken to maintain or improve other stream and watershed characteristics that benefit water quality. The impacts to aquatic life communities observed in this study are the result of inadequate planning and engineering methods of the past. New planning and engineering approaches should be applied to reduce the impact on streams and

accommodate future development. For streams that are already impaired, watershed restoration does not necessarily mean removing large areas of IC. Rather, it could involve a combination of efforts, such as retrofitting and improving existing infrastructure, restoring floodplains and riparian corridors, repairing stream channels and eroding stream banks, and reducing the application of fertilizer, salt, and other chemicals.

Acknowledgement

Funding for this project, in part, was provided by the U.S. Environmental Protection Agency (EPA) under Sections 104b3 and 106 of the Clean Water Act. EPA does not endorse any commercial products or services mentioned.

Contents

Figures

Tables

Appendices

I. Introduction

This study focused on one aspect of urbanization, impervious cover (IC), and its relationship with the condition of aquatic life in streams. IC includes hard surfaces that prevent water from soaking into the ground, such as roofs, pavement, and cement [1]. Many impervious surfaces are designed to rapidly shed water into storm drains that often empty into nearby streams. Runoff from IC can cause larger floods and greater bank erosion than normal and carries sediment, nutrients, and toxic pollutants into streams [2]. Streams with large amounts of IC in their watersheds typically do not support healthy and diverse aquatic communities [3, 4]. A previous study of IC in Maine found that streams with >6% IC within their watersheds had an absence of macroinvertebrates that were pollution-sensitive [4]. Species of fish, macroinvertebrates, and algae that require cold, clean water, intact riparian zones, and good quality habitat are typically unable to survive in urban streams [5-9]. As a result, many urban streams support poor quality aquatic communities consisting primarily of tolerant species [10, 11].

Although IC is commonly used as a surrogate for urban development, IC is only one of many factors that influence stream condition in urban areas. The term “urban stream syndrome” was created to recognize the combined effect of multiple stressors on urban streams [12, 13]. In addition to IC, stream quality is determined by the condition of riparian corridors, flood plains, water flow, water temperature, stream channel and bank stability, in-stream habitat, habitat fragmentation or isolation, specific conductance, nutrient enrichment, and toxic chemicals (Section 2). IC can influence many of these factors, but natural conditions and non-IC stressors also influence the factors and ultimately determine how resilient a stream is to IC. A stream may be more resilient if the other factors are favorable to healthy aquatic communities. In contrast, some streams may be more susceptible to IC if the other factors are not favorable to healthy aquatic communities. Every stream is unique and will have a different combination of favorable and unfavorable conditions, making it more or less resilient to development in its watershed. In general, resource managers should be cautious about focusing watershed protection and restoration only on IC.

One of the most important factors that affects stream resiliency to urbanization is the condition of riparian corridors. Riparian corridors include the forest and wetlands along the stream banks. Healthy riparian corridors are greatly important for maintaining stream condition. Trees and plants in riparian corridors stabilize stream banks, provide shade to maintain cool water, regulate humidity, and provide habitat for terrestrial adults of many aquatic macroinvertebrates, such as mayflies, stoneflies, and caddisflies. Falling leaves provide an important food source for macroinvertebrates in small streams [14] and large woody debris provide valuable habitat [15-17]. Also, riparian corridors can minimize the amount of nutrients and pollutants reaching the stream [18]. In addition, natural riparian corridors and flood plains help regulate stream flow following storms and help prevent habitat degradation caused by storm surges. Developing land within riparian corridors can impact water quality and biological communities. In addition, roads and drainage pipes can provide direct pathways for storm water and pollutants to enter streams, effectively bypassing riparian buffers.

The primary purpose of this project was to determine the relationship of the amount of IC in a watershed upstream of a sample location and the attainment of biological criteria. Maine’s Water Classification Program (38 M.R.S.A. Section 464 et seq.) has four classes for streams, including AA, A, B, and C, with different environmental goals and expectations. Every stream segment in the state was assigned to one of those four classes by the State Legislature in the 1980s. Each class has a set of water quality standards and supporting criteria, such as dissolved oxygen and biological criteria. Classes AA and A have the highest environmental expectations and allow the fewest amount of permitted activities, such as dams and wastewater discharges. Class B has lower environmental expectations and allows more permitted activities. Class C has the lowest expectations but the streams must still support all indigenous fish species and maintain the structure and function of resident biological communities. We collected macroinvertebrate and/or algal samples from streams to determine if they attain biological criteria of the assigned class. We analyzed the attainment of biological criteria with the % IC within stream watersheds and within riparian buffers of different widths.

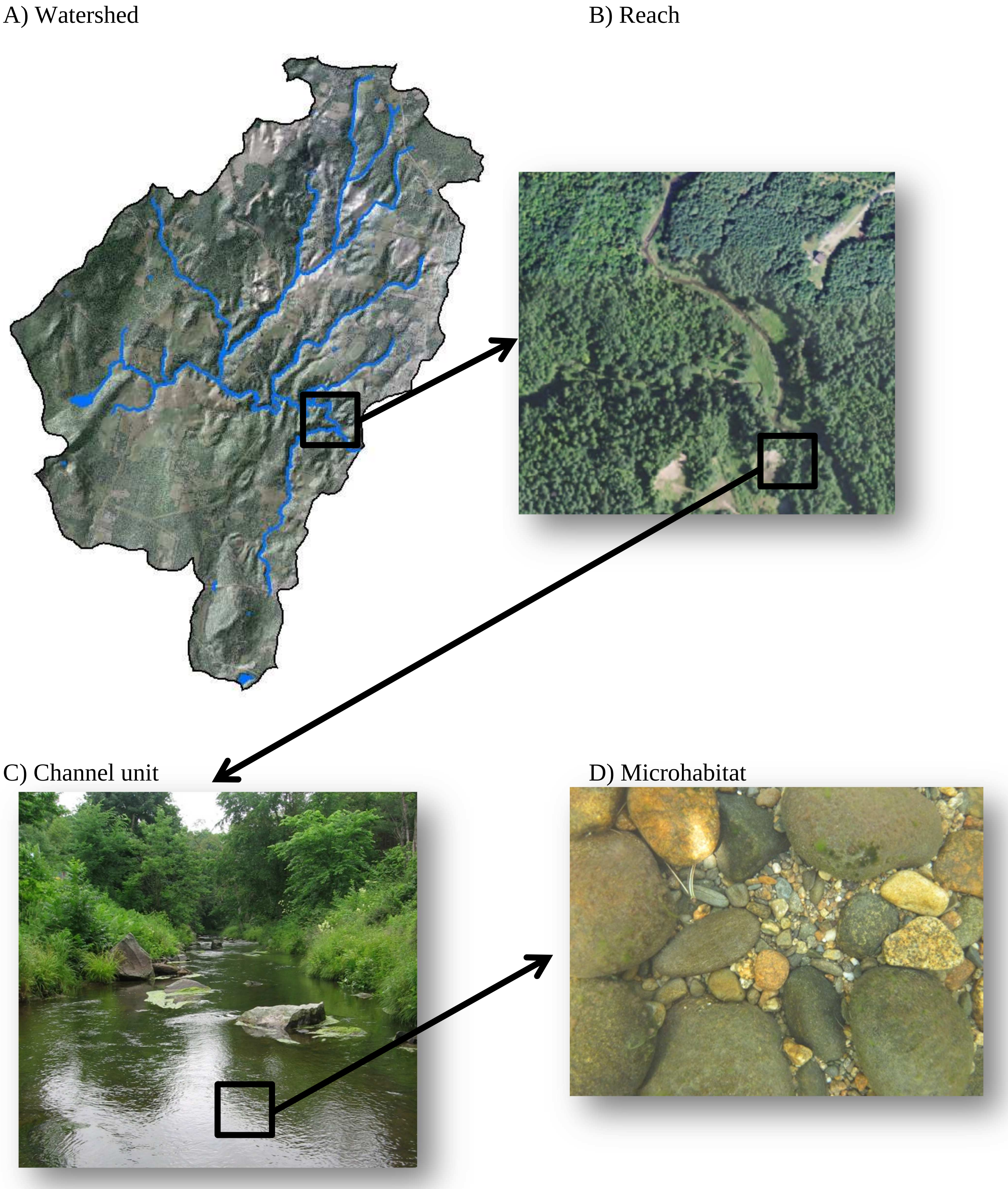


Figure 1. Hierarchical landscape view of stream habitat with the following levels: A) watershed, B) reach, C) channel unit, and D) microhabitat

II. Stream resilience of urbanization

A variety of factors determine the capacity of stream aquatic communities to resist negative effects of urbanization. These factors can be grouped along a spatial scale from coarser to finer levels: a) watershed, b) reach, c) channel unit, and d) microhabitat (Figure 1) [19]. Factors at coarser scales, such as the watershed level, can affect all of the finer scale levels. For example, land use at the watershed level can increase peak flood runoff, which can increase flood intensity at the reach level, which can increase stream bank erosion at the channel unit level, which can increase the amount of fine sediments at the microhabitat level. In general, larger organisms, such as fish, respond more to reach level factors than smaller organisms, such as algae. For a microscopic organism, the microhabitat factors are probably the most important.

Watershed level

At the watershed level, the factors that determine which species of fish, algae, and macroinvertebrates can live in a stream include climate, geology, topography, and human activity (Table 1). Climate determines seasonal variation in temperature, precipitation, frequency of floods and droughts, and stream flow. The atmosphere also transports and deposits nutrients, dust, mercury, and acid rain. Geology and groundwater influence water temperature and chemistry, such as pH, alkalinity, conductivity, and availability of nutrients. For example, a minimally disturbed stream in a watershed with calcium rich limestone geology would have greater pH, alkalinity, and conductivity than a minimally disturbed stream with granitic bedrock. Similarly, watersheds in the coastal plain with ancient marine sediments would have more clay particles and turbidity than watersheds with granitic bedrock. Human activity in a watershed has great potential to impact aquatic life through urbanization, agriculture, habitat fragmentation, and barriers to movement.

Table 1. Watershed-level factors that influence stream health and affect vulnerability of aquatic communities to the negative effects of urbanization

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
Climate and atmosphere	• Clean air • Stable climate	• Acid rain • Atmospheric deposition of nutrients such as nitrogen and phosphorus • Atmospheric deposition of toxic pollutants, such as mercury • Increased air temperature • Large changes in precipitation form, amounts, or timing • Increased frequency and severity of floods or droughts
Land use	• Development, IC, and agriculture is located away from stream channel, riparian corridor, flood plain, and associated wetlands • Headwater and intermittent streams associated with the larger stream remain	• Development, IC, and agriculture is located near the stream or in the riparian corridor, flood plain, and associated wetlands [20] • Headwater and intermittent streams are altered, piped, or filled [20, 21]

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
	intact • Wetlands are protected and remain in good condition • Road crossings are minimized and have properly sized culverts, preferably open-bottom arch culverts that span the stream and flood plain • Storm drains and parking lots use level spreaders, groundwater infiltration, detention ponds, or other best management practices to treat stormwater and/or prevent stormwater from directly entering	• Wetlands are degraded or destroyed [22] • Many roads cross the stream and do not have proper culverts [20, 23] • Storm drains and IC deliver untreated stormwater directly and quickly to the stream [2, 20] • IC prevents infiltration of water into the ground thereby reducing base flow during dry periods [2] • Natural habitat is fragmented into small patches [23] • Logging in steep watersheds increases runoff and downstream erosion
Habitat fragmentation or isolation that limits dispersal or colonization of aquatic life (Watershed and Reach Levels)	• Headwater streams are in good condition and provide potential for recolonization of aquatic life • Downstream rivers are in good condition and provide potential for recolonization of aquatic life • Dams are absent or have fish ladders • Road culverts provide adequate passage for fish and other aquatic life • Neighboring streams and rivers are in good condition and provide recolonization potential to flying, adult stages of many aquatic insects	• Headwater streams are in poor condition or have been piped or buried [21, 24] • Downstream waterbodies are in poor condition • Dams prevent movement of fish and other aquatic life and increase water temperature [25] • Road culverts do not provide adequate passage for fish and other aquatic life • Neighboring streams and rivers are in poor condition [26] • Stream discharges directly into the ocean or an estuary, thereby limiting colonization potential
Community awareness and support	• Community values stream • Watershed association helps maintain awareness and is an advocate for the stream • Stream has realized recreational or educational value, such as fishing, exploring, walking path, field trips, etc.	• Stream is not valued • No watershed association • Stream is not perceived as having recreational or educational value

Reach level

At the reach level, the factors that determine aquatic community composition include valley width and slope, lithology, channel morphology, land use, barriers to movement, and other human activities (Table 2) [19]. Valley width, channel confinement, and slope determine flood intensity, channel morphology, and access to floodplains, which in turn affect channel unit and microhabitat characteristics. For example, a high gradient stream in a confined valley typically will have coarser substrate compared to a low gradient stream with a large flood plain and sandy substrate. Many urban stream reaches were physically altered in the past. In extreme cases, some of Maine’s urban streams have been lined with granite blocks, placed into concrete channels, or buried in underground stormwater pipes. Many streams in Maine were widened and straightened to accommodate historic log drives or saw mills. Lithology is based on the types of rock, such as igneous, sedimentary, and metamorphic, which help determine the sediment size and water chemistry. Land use in riparian corridors has a large role in determining stream condition, as discussed above. Other human activities, such as dams, culverts, barriers to movement, and point source discharges also dictate habitat types and water quality.

Table 2. Reach level factors that influence stream health and affect vulnerability of aquatic communities to the negative effects of urbanization.

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
Valley width and slope	• Larger streams and rivers are potentially less vulnerable and more resilient to urbanization • Low gradient can decrease vulnerability to erosion • Broad valleys with floodplains decrease erosive power of peak flows • Streams have natural connection to flood plains • Steep gradient reaches and riffles help oxygenate water • Broad valleys with many wetlands may increase the concentration of dissolved organic matter that may buffer nutrient enrichment	• Smaller streams are potentially more vulnerable and less resilient to urbanization • Steep gradient can increase vulnerability to erosion [27] • Confined valleys without floodplains have greater erosive power of peak flows [27] • Streams are disconnected from floodplains because of constructed berms or channel incision • Low gradient reaches with still water will oxygenate water less • Broad valleys with many wetlands may decrease water pH, increase water temperature, and decrease dissolved oxygen
Lithology	• Calcium from certain sedimentary rocks can bind dissolved phosphates and reduce risk of eutrophication • Iron and aluminum from igneous rocks and sediment can bind dissolved phosphates and reduce risk of eutrophication • Bedrock and boulders are less vulnerable to erosion • Sand and gravel aquifers and other sources of groundwater help keep stream water cool and dissolved oxygen plentiful	• Large proportion of silts and clays can increase suspended solids and turbidity • Marine deposits that are low in calcium, iron, and aluminum could make surface waters more vulnerable to eutrophication • Sand and fine sediments are more vulnerable to erosion [27] • Reach is downstream of an impoundment, pond, or wetland and has warmer water with less dissolved oxygen • Some sedimentary rocks increase conductivity of water, increasing the vulnerability to anthropogenic sources of conductivity
Channel morphology	• Stream channel is allowed to naturally shift position laterally over time • Stream channel follows natural sinuous course and has proper width and depth • Stream banks are protected by native vegetation allowed to grow to full height • Intact floodplains dissipate energy of flood water • If necessary, eroding stream banks are reshaped, revegetated, or protected with techniques that use natural wood • Stream reach has a variety of habitats	• Frequent surges of stormwater from impervious surfaces with inadequate detention, which erodes stream banks and damages habitat through regular disturbance of the substrate as well as down cutting, stream bank erosion, and/or channel widening [2, 3, 26] • Land adjacent to stream is developed and attempts are made to prevent natural channel migration • Stream bank is “armored” with rip-rap and boulders, which can exacerbate

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
	because of variation in channel dimensions, water depth, water velocity, substrate size, and large woody debris	erosion elsewhere and restricts self-forming alluvial processes • Stream has little habitat diversity because of uniform width, depth, and substrate
Hydrology	• Stream flow varies normally with changes in precipitation, snow melt, and periods of dry weather • Dams are managed to mimic natural hydrographs • Water is withdrawn from stream or nearby wetlands during wet seasons and is stored for later use • Groundwater seeps provide refuge during warm periods for species requiring cold water • Riffles and turbulence oxygenates waters	• Dams create impounded areas that do not function well as either a river or a lake • Some dams unnaturally regulate downstream flow • Dams disrupt natural alluvial processes and sediment transport • Water level in summer is lower than normal because IC prevents water from infiltrating into the ground [2, 3] • Water is withdrawn from stream or nearby wetlands during dry seasons • Still water that results in low levels of dissolved oxygen
Land use in riparian corridor	• Riparian corridors remain intact, filter pollutants, and buffer the stream from development [23, 24] • Leaves of native trees and shrubs provide an important source of food to aquatic life • Stream is shaded, has cool water, and provides plenty of dissolved oxygen to aquatic organisms • Native vegetation provides habitat for terrestrial, adult life stages of many aquatic insects • Flood plains remain intact, prevent floods, and provide seasonal habitat to many aquatic organisms • Dead trees, branches, and other large woody debris accumulate in stream and riparian corridor	• Development encroaches on riparian corridor [5] • Vegetation in watershed and riparian corridor is fragmented into small patches [25] • Stream is not shaded, has warm water, and provides less dissolved oxygen to aquatic organisms [2, 3] • Trees and shrubs are removed and no longer shade the stream, provide food to aquatic life, or provide habitat for adult life stages of many aquatic insects [2, 3] • Non-native vegetation proliferates • Riparian corridors are manicured or replace by lawn [26] • Flood plains are altered or disconnected from the stream • Large woody debris is absent [15-17] • Roads and storm drains bypass riparian buffer and carry untreated stormwater directly to stream [2, 27-29] • Lights along roads and developed areas alter life cycles, dispersal, and survival of adult stages of aquatic insects [30]
Other human activities	• Steps have been made to minimize impact from human activities in watershed	• Poorly treated point source discharges, such as treatment plants, factories, mills, food processing plants, and hatcheries • Contaminated groundwater from salt, nitrates, and soluble pollutants • Chloride from road salt, unprotected sand and salt piles, and contaminated groundwater [31-40]

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
		• Improperly sized or installed culverts create barriers to aquatic life movement, • Improperly sized or installed culverts impound water upstream and/or cause erosion downstream during peak flows • Water withdrawal directly from stream or indirectly through nearby wells • Chemical and fuel spills contaminate surface water and groundwater [28, 29] • Airport deicer chemicals [30] • Large quantity of litter and solid waste in stream

Channel unit level

Channel width, depth, and shape are important factors at the scale of the channel unit (Table 3). Pool depth, substrate size distribution, interaction with groundwater, and large woody debris also determine habitat availability and quality for different species. Channel unit characteristics can be directly altered by human activities, such as channelization, channel straightening, and armoring stream banks. In addition to direct alteration, channel morphology can be altered by human activities at the watershed and reach levels. For example, stormwater runoff from impervious cover can increase peak flow and change channel unit morphology.

Table 3. Channel unit level factors that influence stream health and affect vulnerability of aquatic communities to the negative effects of urbanization.

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
Channel dimensions	• Channel has natural channel dimensions given its position in the landscape, slope, substrate, and water flow • Stream has unimpeded access to intact floodplains	• Channel is overly widened and flattened from excessive peak flows or historic alteration • Channel is incised • Stream banks are actively eroding • Water depth is very shallow during base flow limiting habitat availability • Channel is too narrow or has an unnatural channel dimensions because of granite blocks, rip rap, or concrete • Channel is buried in a culvert or stormwater pipe
Habitat	• Rocks, boulders, and logs provide variety of microhabitats and protection from floods • Undercut banks and tree roots provide	• Naturally rocky substrate with boulders and cobble is buried or embedded by fine sediment • Substrate is uniform, providing little

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
	habitat for fish and macroinvertebrates • Stream has variety of depths and water velocity	microhabitat diversity • Stream has uniform depth and velocity • Substrate consists of silt and clay which increases turbidity and damages gills

Microhabitat level

At the microhabitat level, the most important factors are microtopography and water quality (Table 4). Similar to the channel unit level, human activities can directly alter microhabitat, such as placing rip rap in a stream. Microhabitats can be indirectly altered by human activities at coarser spatial scales. For example, sediment from farm fields, construction sites, or eroding stream banks can fill spaces between rocks a reduce habitat quality for certain species of fish, algae, and macroinvertebrates. Human activities at the watershed and reach levels affect water quality. For example, application of road salt increases stream conductivity and chloride concentrations.

Table 4. Microhabitat level factors that influence stream health and affect vulnerability of aquatic communities to the negative effects of urbanization.

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
Microtopography	• Boulders, cobble, and large woody debris provide habitat diversity for fish, salamanders, and macroinvertebrates • Stable substrates provide better habitat for algae • Open spaces between rocks provide habitat for macroinvertebrates, fish, and salamanders	• Predominance of sand, silt, or clay provides little habitat diversity for macroinvertebrates • Unstable substrates provide poor habitat for algae • Rocks are embedded or buried by fine sediment • Excessive growths of algae or filamentous bacteria, such as sewage fungus or iron bacteria, clog spaces between rocks and decrease habitat quality for macroinvertebrates • Excessive water velocity scours or moves substrate
Water quality	• Natural amounts of dissolved ions are in the water • Specific conductance is typically <200 µS/cm • Low amounts of dissolved ions allow natural functioning of gills and other bodily processes of freshwater species typically found in Maine • Low concentrations of nutrients, typically <30 parts per billion of total phosphorus and <1 part per million of total nitrogen	• Specific conductance is > 300 µS/cm in base flow [41-43] • Specific conductance is much higher (>1,000 µS/cm) after snow melt or spring storms [44-46] • Dissolved ions disrupt natural functioning of gills and other bodily processes of aquatic life • Chloride from road salt, unprotected sand and salt piles, and contaminated groundwater [31-40]

Factor	Conditions that will promote healthy aquatic communities or make streams less vulnerable and more resilient to urbanization	Conditions that will harm aquatic communities or make streams more vulnerable and less resilient to urbanization
	• Water is consistently cool and well oxygenated • Water is clear • Moderate amounts of plants, moss, and algae oxygenate water through photosynthesis • pH is between 6.5 and 8.5	• Stream is enriched with phosphorus and nitrogen, leading to excessive growth of algae, which can clog habitat and cause problems with dissolved oxygen and pH • Water is consistently or periodically warm • Water is turbid, which limits light penetration and harms gills • pH is <6.5 or >8.5

III. Methods

Samples

The Biological Monitoring Unit queried its database to identify macroinvertebrate and algal sample locations with upstream watersheds less than 30,000 acres. We selected this size limit because larger rivers in Maine with watersheds greater than 30,000 acres typically have forested headwaters and IC represents only a small percent of watershed area. In contrast, smaller streams in Maine are more susceptible to urbanization because IC can represent a large portion of watershed area. We excluded samples that were primarily impacted by stressors not related to IC, such as intense agriculture, point source discharges, mine drainage, drought, atypical habitat, and impoundments. We exported data for sites that met these criteria, including attainment of biological criteria. Classes AA and A were grouped for this analysis because they share the same biological criteria.

Impervious cover (IC) estimates

Watershed % IC estimates were computed in ArcMap with 1-meter resolution spatial data from 2004 and 2007. Samples collected before 2006 were matched with 2004 IC data and samples collected in 2006 or later were matched with 2007 IC data. Following Morley and Karr [6], we also created riparian buffers and local buffers within each watershed. The riparian buffers included a fixed width on either side of the stream channel extending from the sample location all the way up the watershed (Figure 2). The local buffers are the same as the riparian buffers, but extend only 1 km upstream. In addition to computing riparian and local buffers of 200 m width, we computed riparian and local buffers of 100 m, 50 m, and 75 ft (22.86 m), which is associated with the Maine Natural Resource Protection Act.

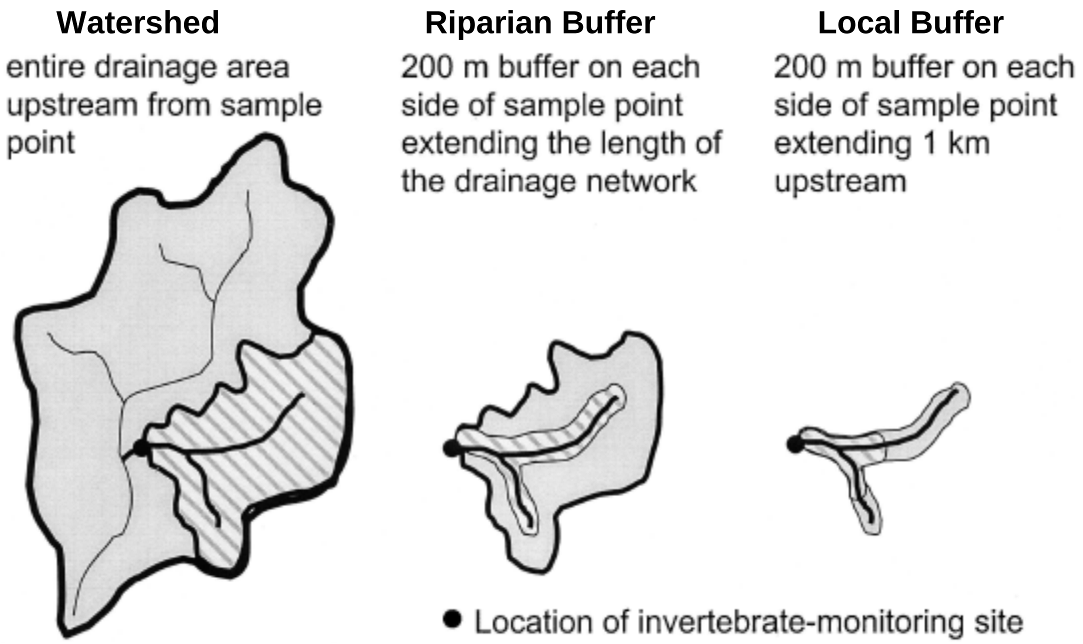


Figure 2. Diagram of watershed, riparian buffer, and local buffer as defined by Morley and Karr [6]. *In each drawing, the area with diagonal lines represents the area included in analysis.*

Data analysis

The relationship between % IC and biological communities was evaluated using three methods: 1) attainment of biological criteria associated , 2) change points associated with community metrics, and 3) community threshold response. In addition, we evaluated the influence of % IC of each of the eight buffer options on aquatic life. All statistical analyses were performed with R version 2.13.1 [47] with the Tinn-R editor [48].

1) <u>Attainment of biological criteria in relation to watershed % IC</u>

We evaluated the relationship between watershed % IC and attainment of biological criteria by grouping samples by their attained class (AA/A, B, C, NA) and calculating the percentiles of % IC within each class. We hypothesized that the % IC values would be smallest in the Class AA/A group and progressively greater with the NA group having the highest % IC values. To determine if the ranked values of the four groups were statistically different, we used a Kruskal-Wallis test, which is the non-parametric equivalent of an Analysis of Variance (ANOVA). For Classes AA/A and B, we defined the watershed % IC target ranges using the 75th-90th percentiles of streams that attain Classes AA/A and B, respectively. For Class C, we set a watershed % IC target at the 75th percentile because of the small number of samples that attained Class C. The Kruskal-Wallis test of the four groups (AA/A, B, C, and NA) indicates if there is a significant difference in ranked values of the groups, but does not indicate which groups are significantly different. In order to more clearly identify distinct groups, we did Kruskal-Wallis tests comparing % IC of the AA/A group vs. B group, B group vs. C group, and C group vs. NA group.

We computed the probability of attaining classes AA/A, B, and C over the gradient of watershed % IC by grouping samples based on whether they attained a certain class or not; first for macroinvertebrates and then for algae. For each class, we used logistic regression with watershed % IC as the independent variable and the binary values of attaining the class or not as the dependent variable. For each class, the logistic regression produced a graph with a curve showing the predicted probability of attaining the class across the gradient of watershed % IC. For Class AA/A, we assigned a value of 1 to samples that attained Class AA/A and a value of 0 to samples that did not (i.e., Class B, Class C, and NA). For the Class B logistic regression, we assigned a value of 1 to samples that attained Classes AA/A or B, and a value of zero to Class C and NA samples. For the Class C logistic regression, we assigned a value of 1 to samples that attained Classes AA/A, B, or C and a value of 0 to NA samples.

2) Attainment of biological criteria in relation to % IC in riparian buffers

Although, we predicted that the general trend would be to have the lowest watershed % IC in the AA/A group and highest in the NA group, we did not know which buffer width option would best explain attainment of biological criteria. First, we created a correlation matrix to examine relationships of the % IC of whole watersheds with % IC within each of the eight buffer options. Next, we repeated the process of comparing % IC means of the four groups followed by the three pairwise comparisons for each of the riparian buffer options (e.g., 50 m buffer, 100 m buffer). For each of the buffer width options, we determined if the mean % IC values of the four groups were statistically different from each other (Kruskal-Wallist test) and which of the four groups were distinct from the others. For each of the buffer widths options, we also computed the probability of attaining classes AA/A, B, and C as described above. We identified buffers with the strongest response to IC as the ones with the least residual variance of the logistic regression models.

3) Metric change points

The third method was to examine the relationship between % IC and community metrics for macroinvertebrates and algae by plotting % IC with the community metrics and identifying change points. Change point analysis searches for the value of % IC with the greatest shift in a metric's values. For each value of % IC in the data, change point analysis splits the data into two groups with one group having all samples with % IC less than that value and the second group having all samples with % IC greater than that value. It then computes the mean of the community metric of the two groups (lower % IC group and higher % IC group). The change point is the value of % IC with the greatest difference in the two means.

We computed the following five macroinvertebrate metrics [49] :

- *EPT relative richness*, which is the number of different mayfly (Ephemeroptera), stonefly (Plecoptera), and caddisfly (Trichoptera) genera divided by the total number of genera
- *Hilsenhoff Biotic Index* (HBI), which is an indicator of organic enrichment
- *Perlidae abundance*
- *Relative richness of Diptera* (true flies)
- *Relative abundance of Chironomidae* (midges), which was

Previous studies of impervious cover showed that EPT richness decreased and HBI increased in response to more impervious cover [e.g., 4, 50, 51, 52]. We used EPT relative richness rather than EPT richness to avoid penalizing oligotrophic streams with naturally low diversity. We included Perlidae abundance because this family of stoneflies was common in streams that attain Classes AA/A and B, and we expected that it would have a negative threshold response at a smaller % IC than the other metrics [53]. The relative richness of Diptera and relative abundance of Chironomidae were expected to increase with greater % IC and have a greater % IC change point than the previous metrics.

We computed the following five algal metrics:

- *Trophic Index*, which is weighted average index with van Dam Trophic values for diatoms [54].
- *Relative richness of sensitive algal taxa* [8].
- *Relative abundance of tolerant algal taxa* [8].
- *Richness of diatoms that require high oxygen concentrations* [54].
- *Relative richness of motile diatoms* [8, 55], which are thought to be resilient to sedimentation.

The van Dam Trophic Index, relative abundance of tolerant algae, and relative richness of motile diatoms were expected to increase with watershed development [e.g., 8, 55, 56, 57]. In contrast, the relative richness of sensitive taxa and richness of diatoms that require high oxygen concentrations were expected to decrease with watershed development [8, 55].

We evaluated the relationships of watershed % IC and each metric by creating scatterplots with locally-weighted regression lines and computing non-parametric change points [58]. The non-parametric change point method identifies an amount of IC where there is the greatest difference in the metric means on either side of the change point. The statistical significance of the change points was analyzed using chi-squared tests [58]. Randomized bootstrap resampling with 1,000 permutations was performed to estimate variance associated with change points. The method then split the data into a low % IC group and a high % IC group based on the primary change point. We searched for a “secondary change point” within the low % IC group and again within the high % IC group. The ecological importance of metric change points was evaluated by examining patterns in sample attainment (i.e., AA/A, B, C, or NA) on both sides of the change points.

In addition, we plotted watershed % IC and EPT relative richness with the size of the sample points on the graph scaled to represent the % IC within the 50 m riparian buffer. Samples with higher % IC values had larger points on the graphs. We added a red-purple-blue color gradient to correspond to size with samples with red indicating greatest % IC and blue indicating least % IC. We took a subset of data with watershed % IC greater than the change point. We also excluded the two samples with the greatest watershed % IC because they had very large % IC within the 50 m buffer. With the subset of samples, we compared the % IC within the 50 m buffer of samples above the locally-weighted regression line and samples below the regression line. We hypothesized that the samples that had lower EPT relative richness than expected based on watershed % IC (i.e., those samples below the regression line) would have larger % IC within buffers. Conversely, we predicted that samples with greater EPT relative richness than expected based on watershed % IC (i.e., those samples above the regression line) would have lower % IC within buffers. We tested our hypothesis with a Mann-Whitney U test and determined if the median buffer % IC of samples above the line was statistically different than the median buffer % IC of samples below the line.

4) Community threshold responses

To examine shifts in macroinvertebrate and algal community structure in response to % IC, we used Threshold Indicator Taxa Analysis (TITAN) and nonparametric community change point analysis (nCPA) [9, 59]. Macroinvertebrate species abundances were aggregated to the genus level prior to analysis because most organisms were identified to the genus level [49]. Most diatoms were identified to species and many non-diatom algae were identified to genus. We only included taxa occurring in ≥5 samples, resulting in 348 macroinvertebrate genera and families and 209 algal species and genera. Taxa abundances were $\log_{10}$+1 transformed prior to analysis. Macroinvertebrate and algal data were analyzed separately. For each taxon, TITAN sequentially computed an indicator value (IndVal) score, which is a measure of the fidelity of group membership. In TITAN, a large IndVal score indicates that a taxon is reliably more common and abundant above or below the candidate change point than on the other side. A small IndVal score indicates similar patterns in occurrence and abundance on both sides of the candidate change point. TITAN assigns taxa IndVals to two groups; group 1 includes taxa having greater fidelity to samples collected from lower % IC watersheds (less urban), and group 2 includes taxa that have greater fidelity to samples from higher % IC watersheds (more urban). TITAN then standardizes IndVal scores using the mean and standard deviations computed from bootstrap resampling (500 permutations). Standardized IndVal scores are called “z scores” with a plus or minus to indicate positive (i.e., increases in abundance, z+) and negative (i.e., decreases in abundance, z-) taxon-specific thresholds. TITAN reports z- and z+ taxa that consistently have similar statistically significant change points in the bootstrap resampling. Taxa with truly unimodal responses typically do not make the final cut because they would not have consistent, statistically significant change points in the same direction (i.e., z+ or z-). The final lists of indicator taxa included those that met the following three criteria: 1) a statistically significant ($p<0.05$) IndVal score, 2) statistically significant IndVal scores for >90% of bootstrap permutations, and 3) the direction of response (+ or -) was consistent for >90% of bootstrap permutations.

TITAN produced two types of graphs to help identify potential community change points. First, we produced plots that display the % IC values of indicator taxa change points, the strength of the change points as represented by z-scores, and uncertainty associated with the change point values. The community change points typically correspond with the % IC value that has many nearby taxa change points. Second, we produced sum[z] plots that show the summed z+ and z- scores of reliable indicator taxa at each potential change point. The largest sum[z-] and sum[z+] scores are interpreted as community change points. In other words, TITAN identified community thresholds along the % IC gradient with greatest loss of z- taxa (those more sensitive to % IC) and the greatest influx of z+ taxa (those more tolerant of % IC).

After identifying the primary change points for macroinvertebrates and algae based on all of the data, we split the data into two groups to determine if there were community response thresholds that were less pronounced than the primary thresholds. First, we repeated the TITAN analysis described above with a low IC group that included samples with % IC < primary change point. Next, we repeated the TITAN analysis with a high IC group consisting of samples with % IC ≥ the primary change point. We used the term “secondary change point” to refer to change points based on the low IC group or high IC group.

IV. Results

1) *Attainment of biological criteria in relation to watershed % IC*

The database search resulted in 140 macroinvertebrate and 90 algal sample sites located across the state representing the full range of IC expected in Maine. Of the 140 macroinvertebrate samples included in the study, 75 attained Class AA/A, 31 attained Class B, 11 attained Class C, and 23 failed to attain Class C and were categorized as non-attainment (NA). Of the 90 algal samples included in the study, 35 attained Class AA/A, 24 attained Class B, 15 attained Class C, and 16 failed to attain Class C and were categorized as NA. In general, watersheds of AA/A samples had the smallest proportion of IC and watersheds of NA samples had the largest proportion of IC (Figure 3). For the macroinvertebrate samples, the median watershed % IC values of groups AA/A, B, C, and NA were 1.0, 3.0, 13.0, and 29.5%, respectively and were not similar ($p<0.001$). For the algal samples, the median watershed % IC values of groups AA/A, B, C, and NA were 0.3, 1.5, 6.3, and 20.3% respectively and were not similar ($p<0.001$). For Class AA/A, the 75th-95th percentiles were 1.0-1.9% for algae and 1.9-3.6% for macroinvertebrates. For Class B, the 75th-95th percentiles for algae and macroinvertebrates were 2.4-3.6% and 4.3-8.7%, respectively. The 75th percentiles for Class C were 16.0% for algae and 17.1% for macroinvertebrates.

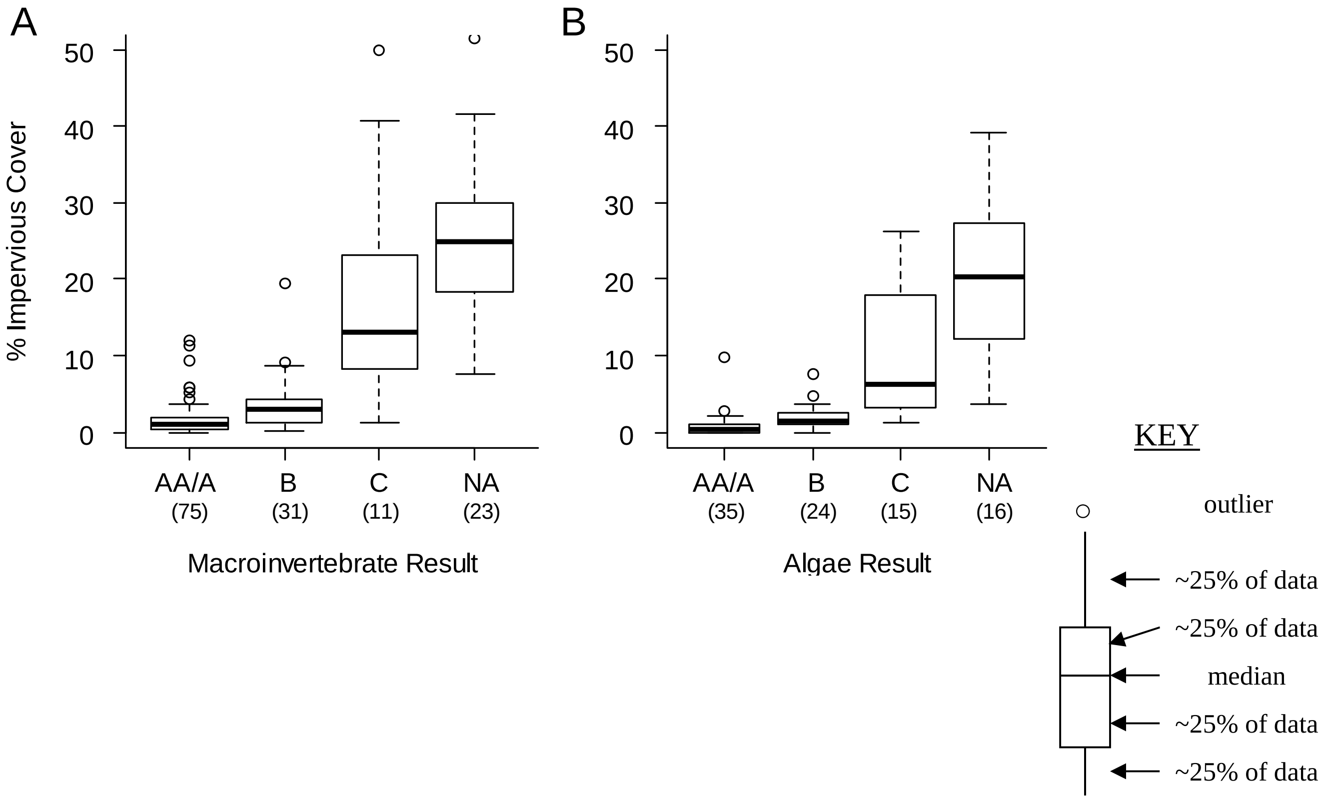


Figure 3. Box-and-whisker plot of watershed % IC of samples grouped by bioassessment results for A) macroinvertebrates and B) algae with number of samples in parentheses. *The non-attainment (NA) group includes samples that do not attain biological criteria for Classes AA/A, B, or C.*

For both macroinvertebrates and algae, the probability of attaining Class AA/A was highest (~0.8) at very low levels of watershed % IC and decreased rapidly with increasing % IC (Figure 4). The probability of attaining Class B approximated 1.0 at 0 % IC and then decreased rapidly. In contrast, the probability of attaining Class C decreased more gradually between 10 and 30% IC for both algae and macroinvertebrates.

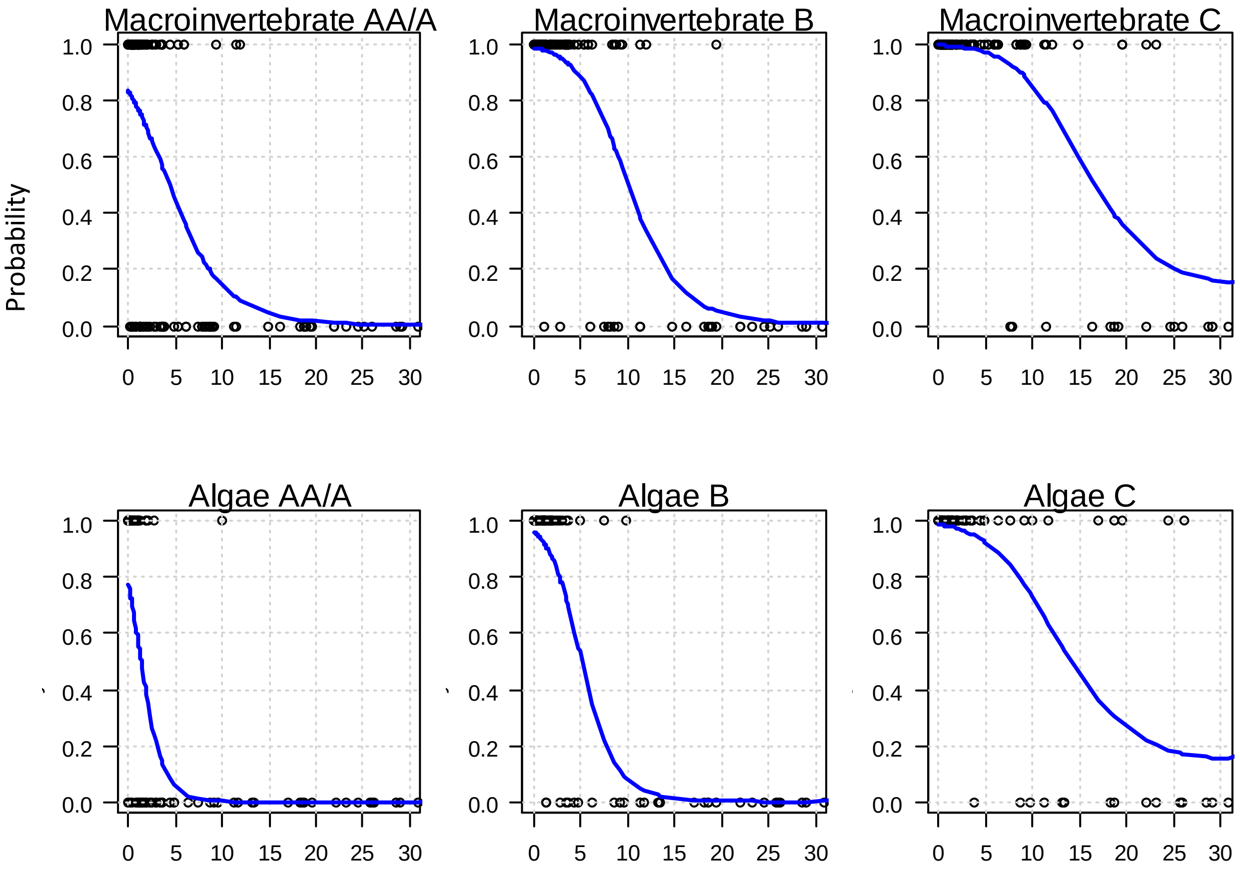


Figure 4. Probability of attaining water quality classes across the gradient of watershed % IC for macroinvertebrates and algae.

2) Attainment of biological criteria in relation to riparian buffers

The % IC estimates for the whole watershed and eight different buffer options were highly correlated with each other, particularly with pairs of buffers with similar width (Figure 5). The logistic regression models showing the probability of attaining biological criteria (i.e., classes AA/A, B, and C) in relation to the % IC within riparian buffers were all worse than the model for watershed % IC (graphs not shown). The models with the least residual variance were consistently the models for the widest buffers (200m, 100m) extending all the way upstream (Table 5). Conversely, the models for narrow buffers (50m, 75 ft) extending only 1 km

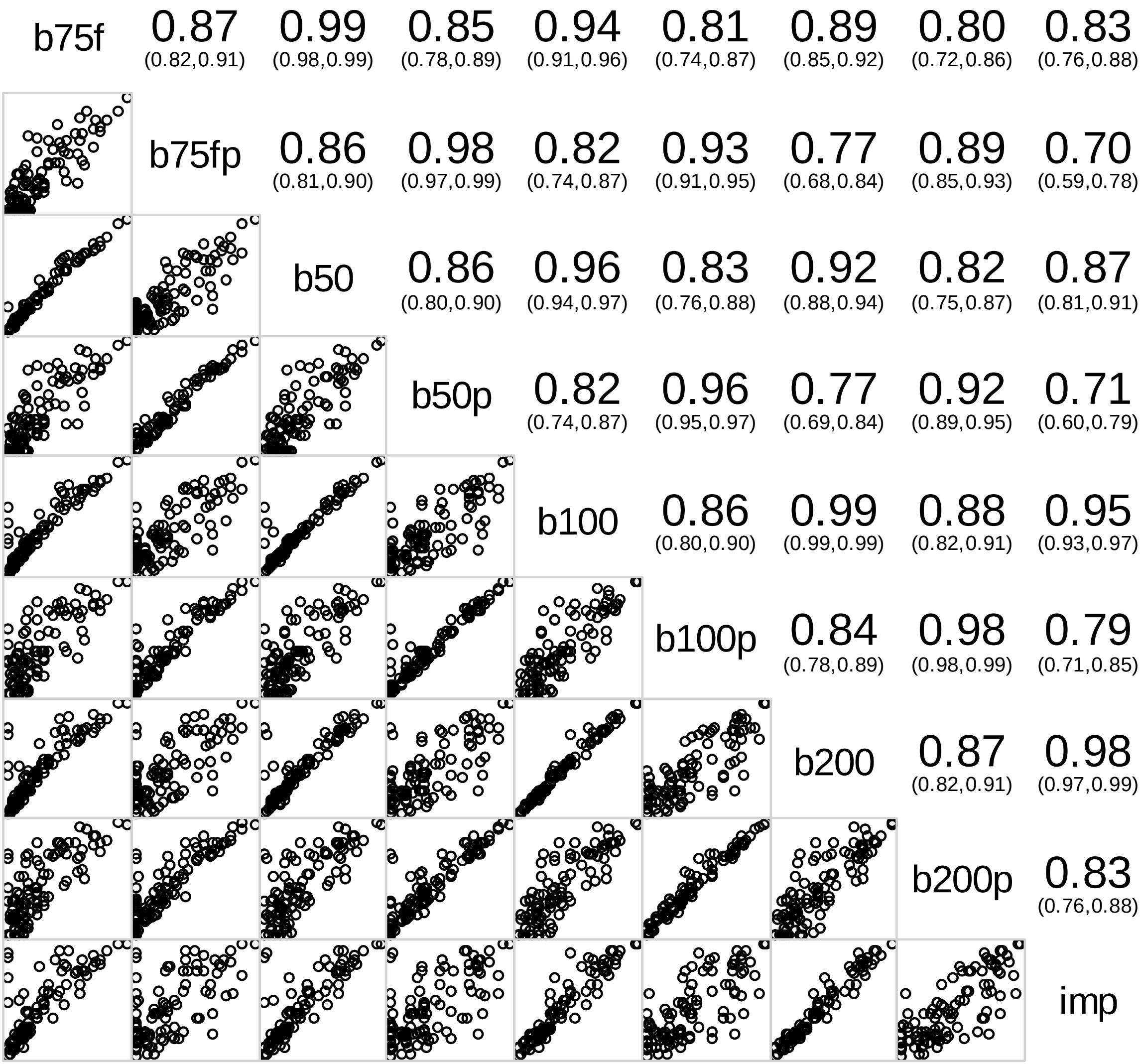


Figure 5. Correlation matrix of % IC within whole watersheds and the eight buffer options. *The codes in the diagonal row from the upper-left to lower-right define the buffer options (b75f = 75 ft buffer extending throughout the watershed upstream of the sample point, b75fp = 75 ft buffer extending 1 km upstream of sample point, b50 = 50 m buffer, b50p = 50 m buffer extending 1 km upstream, b100 = 100 m buffer, b100p = 100 m buffer extending 1 km upstream, b200 = 200 m buffer, b200p = 200 m buffer extending 1 km upstream). The numbers in the upper-right panel are the correlation values with a confidence interval in parentheses. The lower-left panel shows a scatterplot for each pair of buffer options.*

upstream consistently had the greatest residual variance. The patterns were consistent for classes AA/A, B, and C and for both algae and macroinvertebrates, with the exception of the macroinvertebrate model for Class C which had the 200m buffer extending only 1 km upstream as the best model. In summary, the models for the wider buffers extending all the way upstream had more precise estimates than models for narrower buffers. The models for buffers extending only 1 km upstream were consistently the worse than corresponding buffers that extend all the way upstream.

Table 5. Residual deviance of logistic regression models for attainment of water quality classes AA/A, B, and C using different riparian buffers

Class	b200	b100	b50	b75f	b200p	b100p	b50p	b75fp
Macr. AA/A	92	99	107	109	114	121	128	128
Macr. B	48	57	68	74	60	72	82	83
Macr. C	60	63	68	74	57	64	72	74
Alg. AA/A	60	65	67	69	81	85	86	88
Alg. B	39	42	44	49	65	68	73	76
Alg. C	51	54	60	68	62	63	67	69

Macr. = Macroinvertebrate, Alg. = Algae, f = feet, p = watersheds extend only 1 km upstream of sample points

3) *Community metric change points*

The % IC change points identified for the macroinvertebrate and algal community metrics are summarized in Table 6 and Figures 6 and 7. The change points for Perlidae abundance, van Dam trophic index, relative richness sensitive algae, and richness of high oxygen diatoms occurred at the transition of Class AA/A samples to B, C, and NA samples. In other words, most of the Class AA/A samples were to the left of those change points. The change points of EPT relative richness and relative Chironomidae abundance occurred at the transition of Class AA/A and B samples to C and NA samples. In contrast, most of the samples to the right of the change points for Hilsenhoff Biotic Index, relative Diptera richness, relative abundance of tolerant algae, and relative richness of motile diatoms were NA samples. Secondary % IC change points were identified for the following metrics: EPT relative richness (13.3), Hilsenhoff Biotic Index (1.0), Relative Chironomidae Abundance (1.8), van Dam trophic index (2.9), relative richness sensitive algae (11.5), relative abundance tolerant algae (3.6), and motile diatom relative richness (0.3).

Table 6. Change points of macroinvertebrate and algal community metrics.

Metric	% IC change point	Bootstrap median and (interquartile range)	p-value	Mean to the left of c.p.	Mean to the right of c.p.
Perlidae abundance	2.2	2.3 (2.3-2.3)	<0.001	6.7	1.1
EPT relative richness	6.8	7.0 (6.80-13.3)	<0.001	0.42	0.18
Hilsenhoff Biotic Index	14.8	11.7 (7.7-15.5)	<0.001	4.3	6.2
Chironomidae relative abundance	7.8	8.0 (6.0-11.7)	<0.001	0.32	0.57
Diptera relative richness	11.3	7.0 (6.8-13.4)	<0.001	0.38	0.51
van Dam Trophic Index	1.2	1.2 (1.1-2.5)	<0.001	3.2	4.2
Sensitive algae relative richness	1.2	1.1 (1.0-1.2)	<0.001	0.31	0.12
Motile diatom relative richness	9.9	10.6 (6.7-10.6)	<0.001	0.32	0.54
High O_2 diatom richness	1.1	1.2 (0.9-8.1)	0.014	13.6	9.6
Tolerant algae relative abundance	17.0	14.9 (10.5-17.6)	<0.001	0.03	0.25

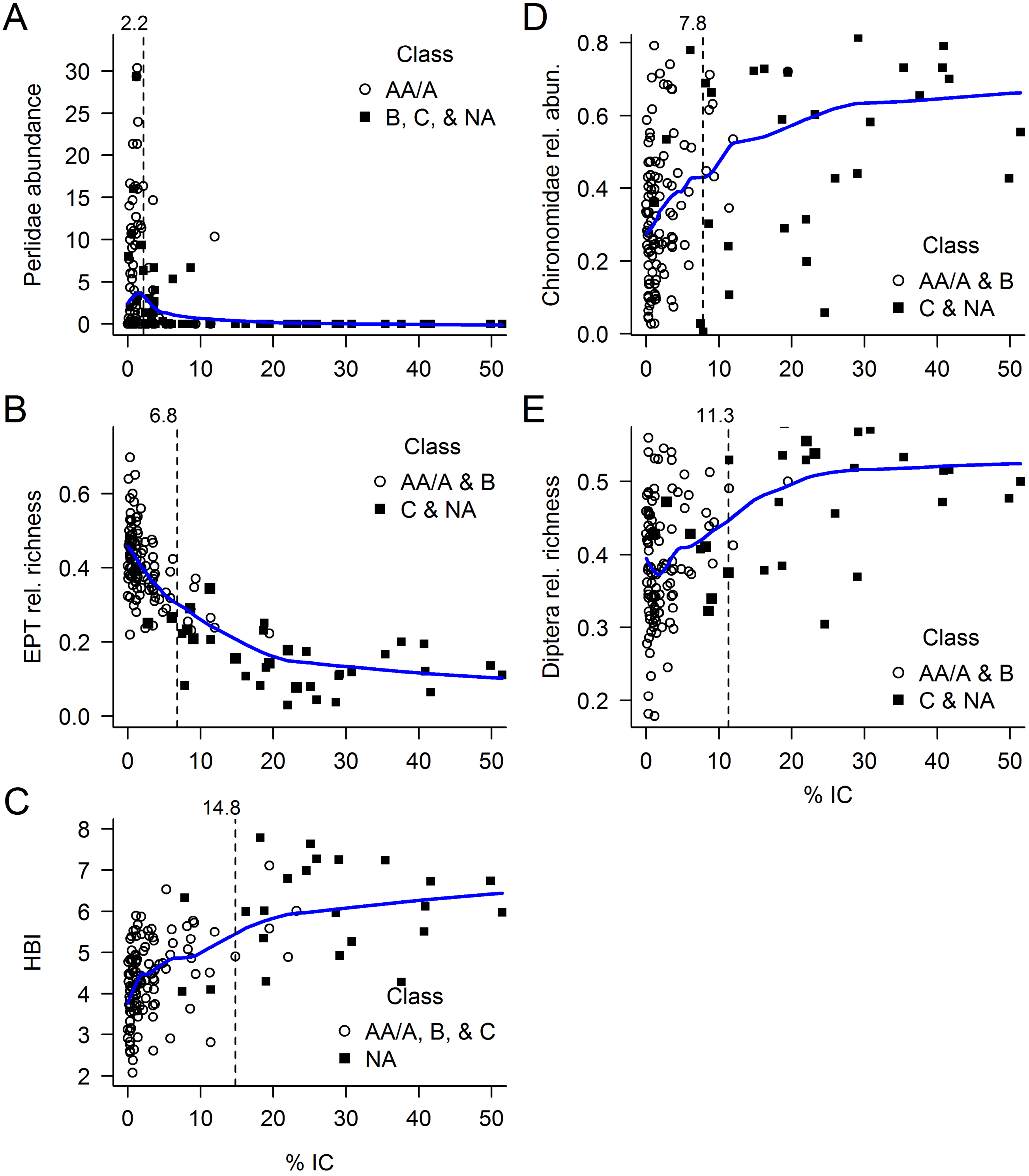


Figure 6. Scatterplots of % IC with A) abundance of stoneflies in the family Perlidae, B) relative richness of mayfly, stonefly, and caddisfly genera (EPT relative richness), C) Hilsenhoff Biotic Index (HBI) of organic enrichment, D) relative abundance of Chironomidae (midges), and E) relative richness of Dipterans (flies). *The curves are locally-weighted regression lines. Vertical dashed lines are the change points.*

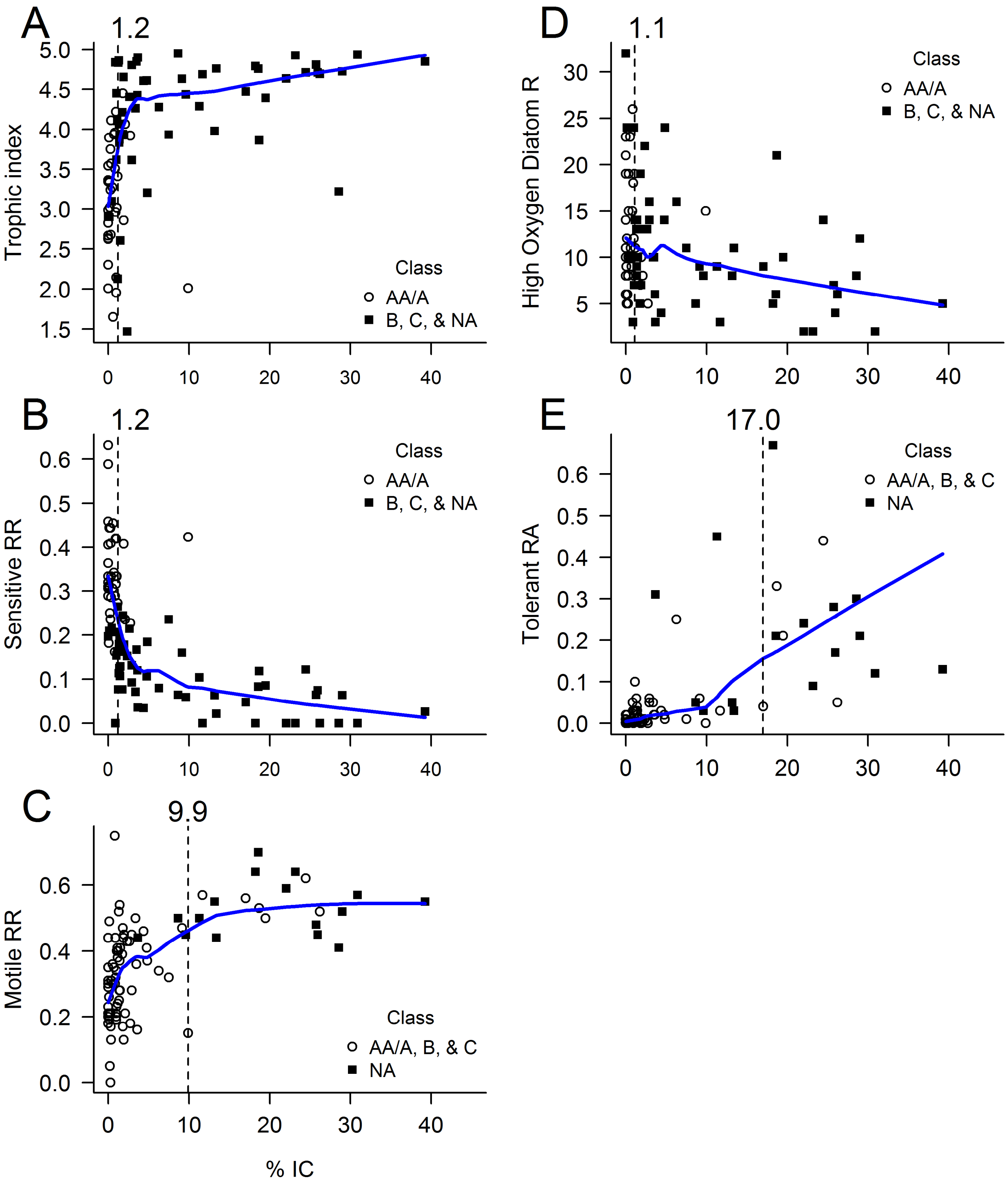


Figure 7. Scatterplots of % IC with A) van Dam trophic index, B) relative richness of sensitive algae, and C) relative richness of motile diatoms, D) richness of high oxygen diatoms, and E) relative abundance of tolerant algae. *The curves are locally-weighted regression lines. The dashed vertical lines are change points.*

The EPT relative richness was influenced by both watershed % IC and buffer % IC (Figure 8). Figure 8 is essentially the same as Figure 6B, but the size and color of the points indicate the amount of % IC within the 50 m buffer. Larger, redder dots have greater % IC within the 50 m buffer and smaller, bluer points have less % IC within the 50 m buffer. When looking at samples to the right of the change point (> 6.8 % IC in watershed), most of the samples that had lower EPT relative richness than expected based on watershed % IC (i.e., those samples below the regression line) had larger % IC within buffers (median=19%). In contrast, samples with greater EPT relative richness than expected based on watershed % IC (i.e., those samples above the regression line) had lower % IC within buffers (median =7%). The medians of the samples above and below the regression line were distinct (chi-squared = 4.8, p=0.03).

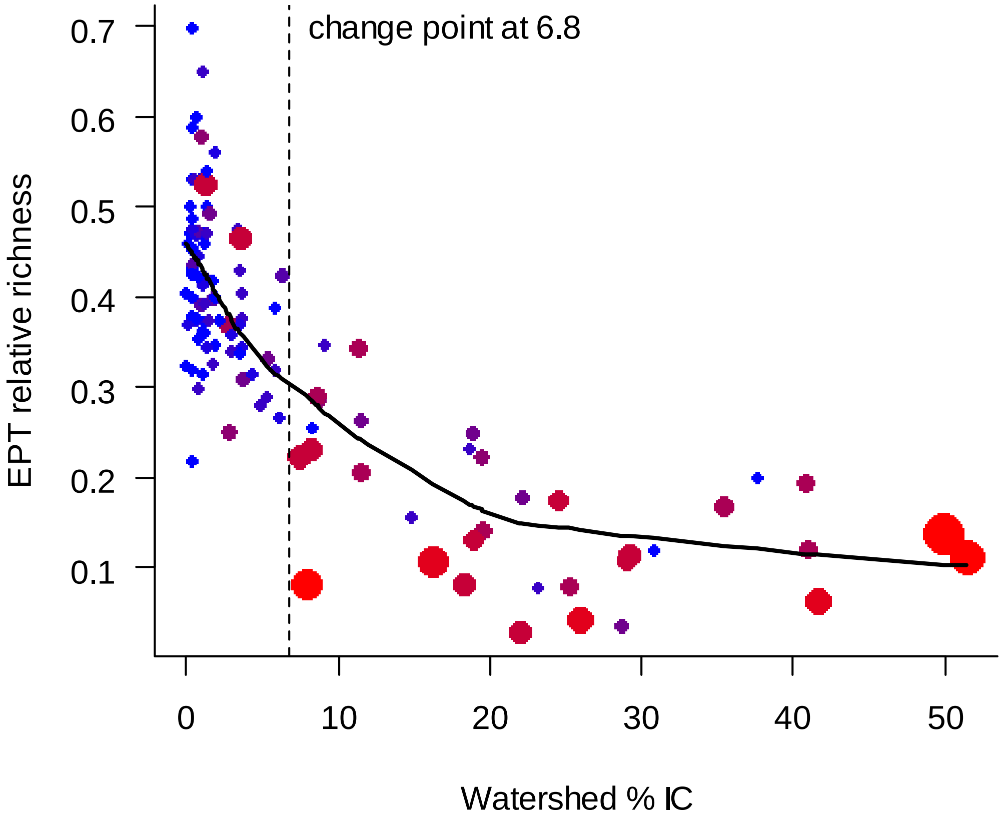


Figure 8. EPT relative richness vs. watershed % IC with points scaled to show the % IC in the 50 m buffer. *Larger, redder points have larger % IC within the 50 m buffer. Smaller, bluer points have less % IC within the 50 m buffer.*

4) *Community threshold responses*

For macroinvertebrates, TITAN identified 51 z- taxa and 41 z+ taxa (Figure 9). Most of the z- taxa were mayflies, stoneflies, and caddisflies (Appendix 1). Half of the z- taxa had change points <8.7% IC and most of the strongest indicator taxa had change points <2.4% IC (Table 7). The z+ taxa mostly consisted of midges, craneflies, beetles, and a variety of noninsects (e.g., snails, worms, isopods, amphipods, leeches) (Appendix 2). Half of the z+ taxa had change points <3.6% IC (Table 7). TITAN identified a macroinvertebrate community threshold based on the loss of taxa that need cold, clean water at 6.8% IC and another community threshold based on the influx of more tolerant taxa at 11.3% IC (Figure 10A). The nCPA found a change point at 11.3% IC, with approximately 80% of the bootstrap permutations resulting in a change point ≤11.3% IC. We used expert judgment to associate the distribution of taxa change points and community thresholds to water quality classes (Table 8).

For algae, TITAN identified 23 z- taxa and 30 z+ taxa (Figure 11, Appendices 3 & 4). Half of the z- taxa had change points <1.2% IC and half of the z+ taxa had change points less than 2.7% IC (Table 7). TITAN identified an algal community threshold based on the loss of sensitive taxa at 1.2% IC and community threshold based on the influx of taxa at 1.9% (Figure 10B). The nCPA found a change point at 2.8% IC, with approximately 50% of the bootstrap permutations resulting in a change point ≤2.9% IC and 90% of the bootstrap permutations resulting in a change point ≤11.5% IC. Similar to the macroinvertebrate results, we used expert judgment to associate algal community results to water quality classes (Table 8).

Table 7. Summary statistics of the % IC change points of taxa identified by TITAN to be reliable z- or z+ indicators.

	n	Minimum	1st quartile	Mean	Median	3rd quartile	Maximum
Macroinvertebrate decreasers (z-)	51	0.3	2.4	7.9	8.7	11.7	20.7
Macroinvertebrate increasers (z+)	41	0.4	1.2	7.7	3.6	11.3	39.2
Algal decreasers (z-)	23	0.1	1.0	4.0	1.2	6.4	20.8
Algal increasers (z+)	30	1.4	1.2	8.1	2.7	8.1	26.1

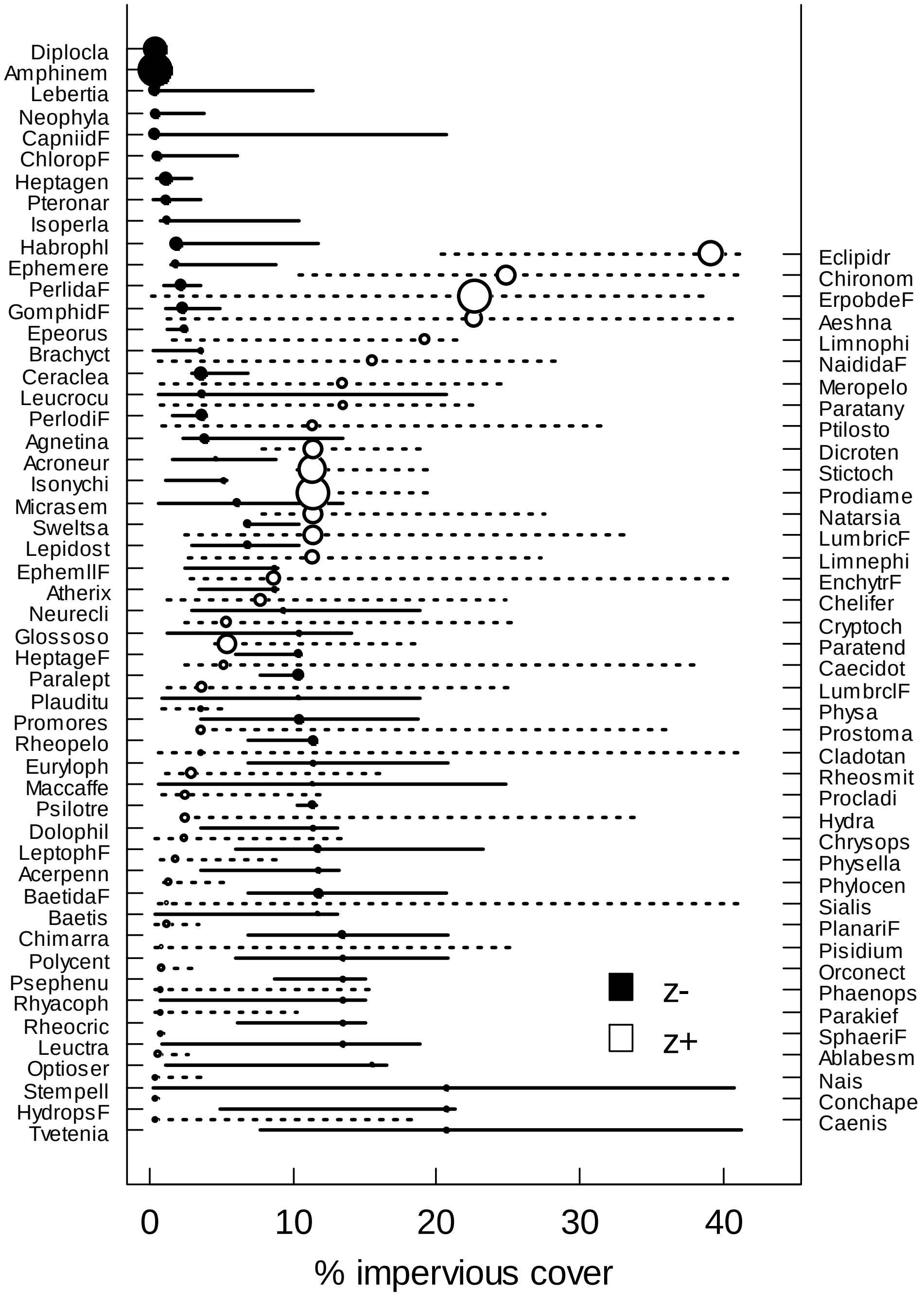


Figure 9. % IC change points for macroinvertebrate taxa identified by TITAN to be reliable z- or z+ indicator taxa. *The z- taxa (black circles) are listed on the left and are the species that decrease in abundance with greater % IC. The z+ taxa (white circles) are listed on the right and are the species that increase in abundance with greater % IC. The location of a circle in relation to the x-axis indicates the % IC value of the change point. Circle sizes represent the strength of the change points (i.e., z score). The horizontal lines represent the 90% confidence intervals associated with the change points. Taxa codes and the corresponding numbers used to create the graphs are listed in Appendices 1 and 2.*

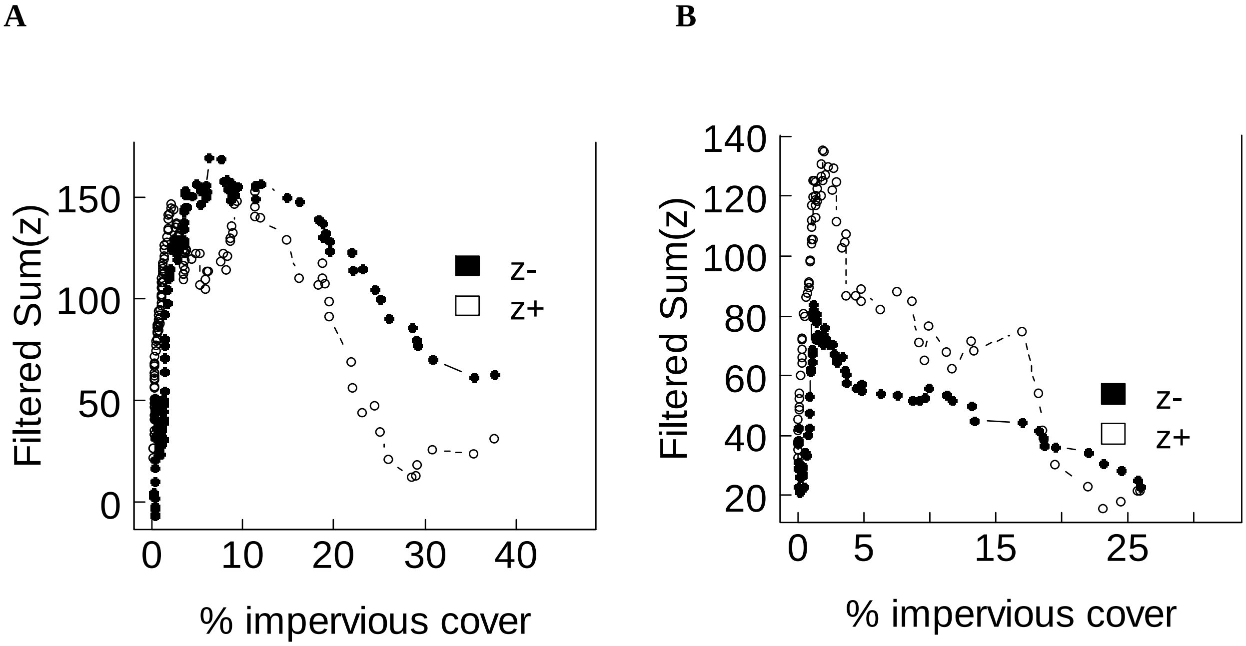


Figure 10. TITAN graphs showing the sum[z-] and sum[z+] values at each potential % IC change point for A) macroinvertebrate genera and families and B) algal species and genera. *Peaks represent largest loss of sensitive taxa (z-, black circles) and largest influx of more tolerant taxa (z+, white circles).*

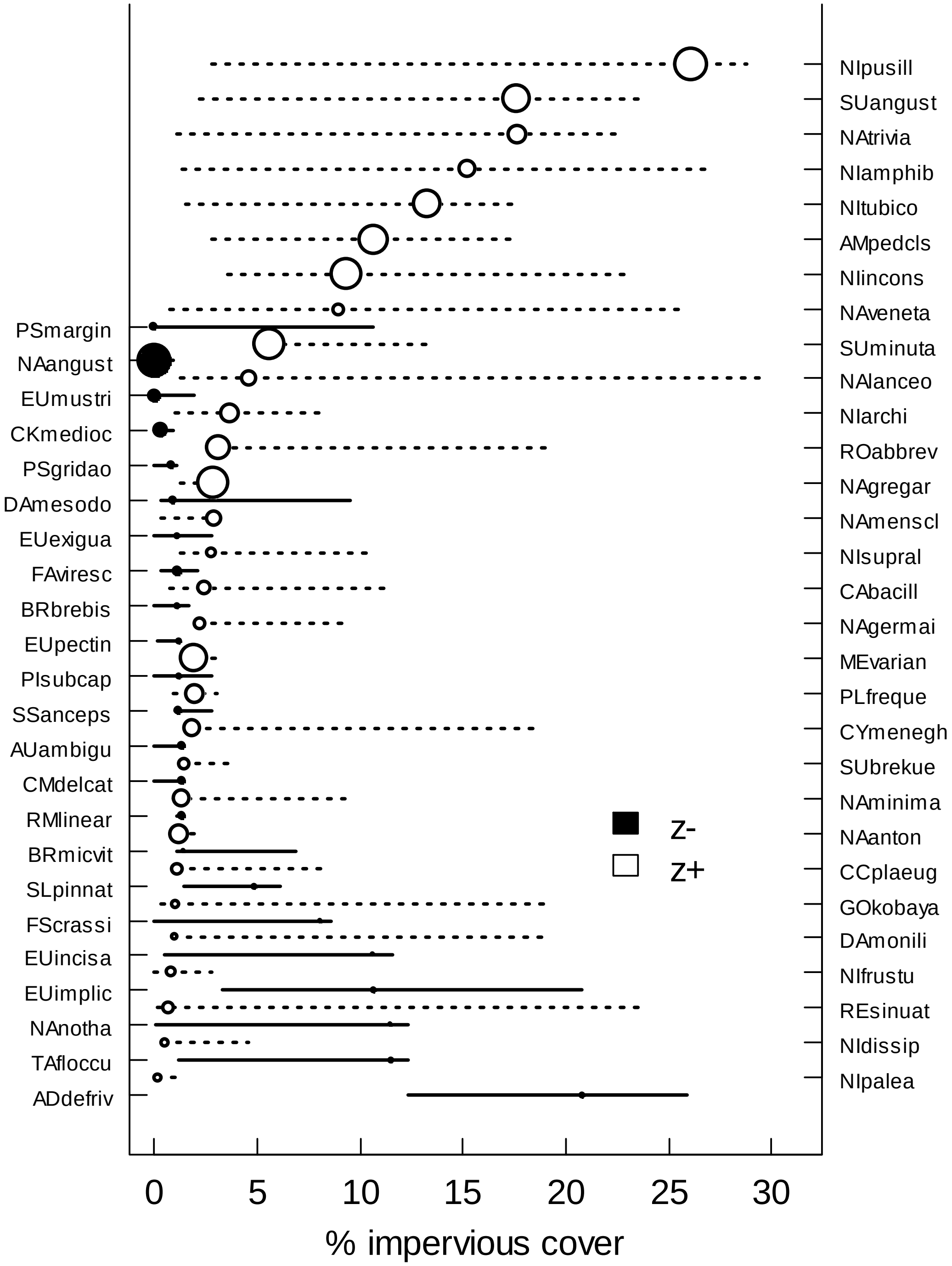


Figure 11. % IC change points for algal taxa identified by TITAN to be reliable z- or z+ indicator taxa. *The z- taxa (black circles) are listed on the left and are the species that decrease in abundance with greater % IC. The z+ taxa (white circles) are listed on the right and are the species that increase in abundance with greater % IC. The location of a circle in relation to the x-axis indicates the % IC value of the change point. Circle sizes represent the strength of the change points (i.e., z score). The horizontal lines represent the 90% confidence intervals associated with the change points. Taxa codes and the corresponding numbers used to create the graphs are explained in Appendices 1 and 2.*

Table 8. Summary of the results showing ranges of % IC targets for supporting biological criteria.

Macroinvertebrate Analysis	**Class AA/A**	**Class B**	**Class C**
1. Percentiles (75th-90th) of % IC values for samples grouped by attained class	1.9-3.6%	4.3-8.7%	17.1% [a]
2. EPT relative richness change point [b]	--	6.8%	13.3% [d]
3. Hilsenhoff Biotic Index (HBI) change point [b]	1.0% [d]	--	14.8%
4. Perlidae abundance change point [b]	2.2%	--	--
5. Relative Diptera richness change point [b]	--	--	11.3%
6. Relative Chironomidae abundance change point [b]	1.8% [d]	7.8%	--
7. TITAN z- indicator taxa [c]	2.3% (25th %tile)	8.7% (median)	11.7% (75th %tile)
8. TITAN z+ indicator taxa [c]	1.2% (25th %tile)	3.6% (median)	11.3% (75th %tile)
9. TITAN sum[z-] thresholds [c]		6.8%	
10. TITAN sum[z+] thresholds [c]			11.3%
11. nCPA threshold [c]			11.3%
Algae Analysis	**Class AA/A**	**Class B**	**Class C**
1. Percentiles (75th-90th) of % IC values for samples grouped by attained class	1.0-1.9%	2.4-3.6%	16.0% [a]
2. van Dam Trophic Index [b]	1.2%	2.9% [d]	
3. Richness of high oxygen diatoms [b]	1.1%	--	--
4. Relative richness of sensitive taxa [b]	1.2%	--	11.5% [d]
5. Relative density of tolerant taxa [b]	--	3.6% [d]	17.6%
6. Relative richness of motile diatoms [b]	0.3% [d]		9.9%
7. TITAN z- indicator taxa [c]	1.2% (median)	6.4% (75th %tile)	--
8. TITAN z+ indicator taxa [c]	2.7% (median)	8.1% (75th %tile)	--
9. TITAN sum[z-] thresholds [c]	1.2%		
10. TITAN sum[z+] thresholds [c]	1.9%		
11. nCPA threshold [c]	2.8%		
Range of % IC with increased risk of not attaining biological criteria	**1-3%**	**3-6%**	**10-15%**

[a] – We used the 75th percentile for Class C because of the small number of samples that attained Class C.

[b] – We used expert judgment to associate change points to the most appropriate water quality class.

[c] – We used expert judgment to associate percentiles and peaks to appropriate classes.

[c] – Secondary change point

V. Conclusions

Greater amount of impervious cover in a watershed upstream of a sample location will have a detrimental effect on aquatic life if steps are not taken to reduce the impact of the IC or improve the condition of other factors (Tables 1-4). For management purposes, we distilled the many results shown in Table 8 into general guidelines based on the risk of a stream not attaining biological criteria associated with Classes AA/A, B, and C (Figure 12). In general, many streams may be unable to maintain Class AA/A biological criteria when watershed IC reaches the range of 1-3% IC (Figure 12). The effects of urbanization are apparent at remarkably low levels of IC if steps are not taken to locate development and IC away from streams, maintain the factors that are promoting healthy aquatic life, and mitigate impacts by improving other factors of stream condition [9, 61]. In general, many streams may be unable to maintain Class B biological criteria when watershed IC reaches 3-6%, although some streams with mitigating factors may support Class B aquatic life at much greater percentages (Figure 12). Some streams will have factors that make them more resilient and other streams will have factors that put them at greater risk. Finally, one would expect many streams to shift from Class C aquatic communities to non-attainment status in the range of 10-15% IC (Figure 12). It is important to keep in mind that the vulnerability of any individual stream to IC depends on other factors in Tables 1-4.

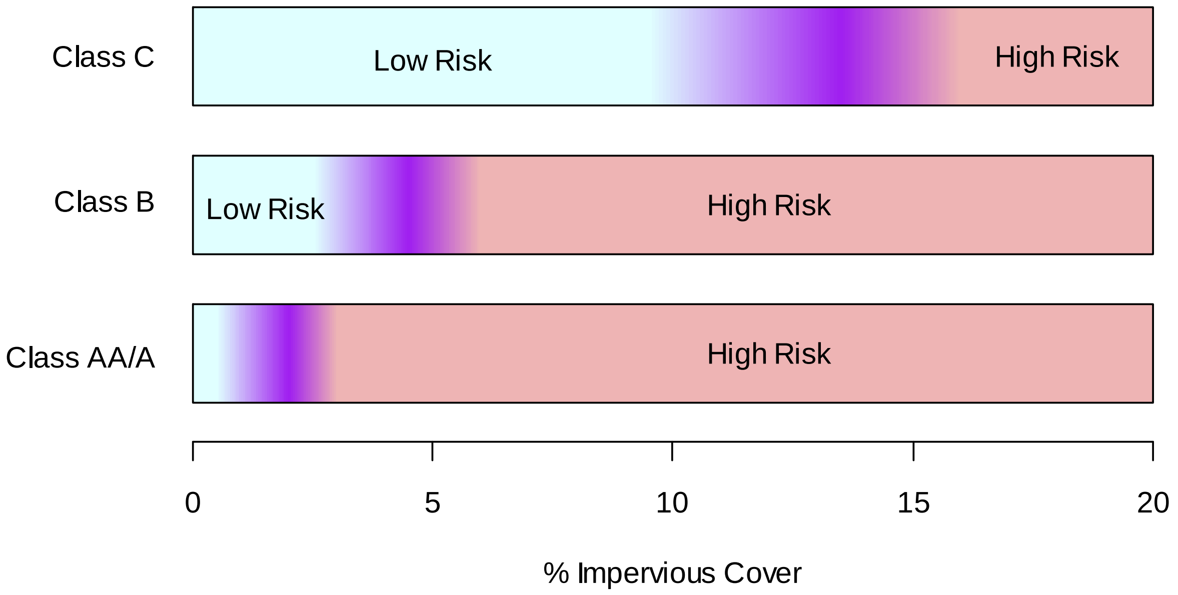


Figure 12. Risk of a stream not attaining biological criteria associated with Classes AA/A, B, and C in relation to % IC in the watershed upstream of the sample location. *Application of the % IC estimates from this study requires use of the same spatial layer. The thresholds identified in the 2012 IC TMDL are different, in part, because the analysis was based on an older 5 m resolution IC spatial layer.*

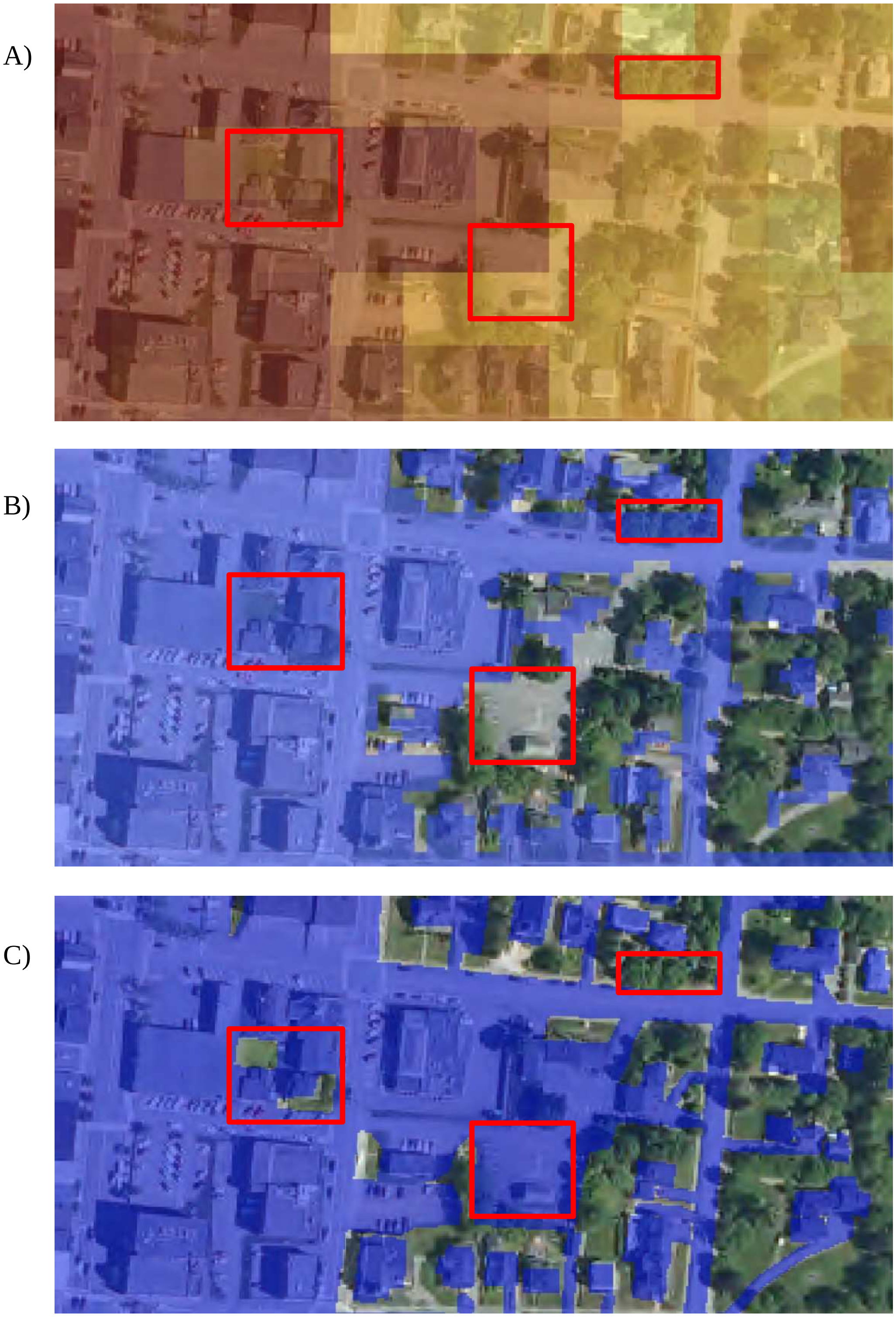
The location of impervious cover in a watershed matters. Generally, it is beneficial to keep IC away from streams and protect undisturbed riparian corridors with native vegetation [5]. The location of impervious cover is most important to streams with moderate amounts of IC in the watershed, as seen by the impact to mayflies, stoneflies, caddisflies (Figure 8). These groups include many sensitive species that require cold clean water and good habitat to survive. Mayflies, stoneflies, and caddisflies make up a smaller than expected proportion of the macroinvertebrate community when there is a large % IC within the 50 m buffer. Protecting natural riparian corridors is important to both preventing stream degradation and restoring stream health.

Further study is needed to better understand the effects of development within riparian buffers on aquatic communities. The results show that % IC within riparian buffers can help explain impacts on algal and macroinvertebrate communities. At low watershed % IC, some development near a stream or river might have little impact. With greater watershed % IC, development within a 50 m riparian buffer is related to a decreased proportion of different mayflies, stoneflies, and caddisflies in the macroinvertebrate community. IC is just one among a wide range of environmental stressors and each stream can be vulnerable to some stressors more than others. For example, a stream that gets water from a groundwater aquifer might be better able to maintain cool water temperature compared to a stream that is an outlet for a pond or wetland. Streams with sandy substrate may experience more stream bank erosion from flood surges than a stream with coarser substrate. In addition, some watersheds may have stressors not directly linked to IC that can damage aquatic life and confound analysis of the effects of % IC on aquatic life, such as groundwater contamination, point sources of pollution, nutrient enrichment, or localized habitat degradation. In general, steps should be taken to maintain or restore native vegetation in riparian corridors and minimize road crossings, storm drains, and gullies that can bypass the riparian vegetation.

Estimates of % IC depend on the spatial resolution of the spatial data. If a spatial layer with coarser resolution is used to estimate % IC, the results are likely to be quite different. The evaluation of the relationship of % IC and stream macroinvertebrate communities in the 2012 *Maine Impervious Cover Total Maximum Daily Load Assessment (TMDL) for Impaired Streams* [60, Appendix 2] used a different spatial layer than this study. Instead of the 2004 and 2007 spatial data with 1 m resolution, the previous analysis was based on 2004 Maine Land Cover Dataset (MLCD) spatial data with 5 m resolution. Figure 13 shows the difference between A) the National Land Cover Dataset (NLCD) with 30 m resolution, which is commonly used by researchers, B) the 2004 Maine Land Cover Dataset (MLCD) with 5 m resolution, and 3) , the 2004 and 2007 spatial data with 1 m resolution used in this study. The NLCD differs from the other two data sources in that each 30 m square in the NLCD has a % impervious cover value ranging from 0 to 100. In general, we found the 1 m resolution data to be the most accurate. Estimates based on the 5 m data underestimated % IC when % IC is less than 2% and overestimated % IC in urban areas when compared to the 1 m data (Figure 14). Although the amount of error in Figure 14 looks uniform because the data were $\log_{10}$-tranformed, the actual amount of error is much greater at larger % IC. It might not necessary, however, to revise the existing IC TMDLs because the measurement of success is restoring water quality and healthy aquatic life communities, not reaching a specific IC target.

Many impacts to aquatic life communities observed in this study were the result of historic, inadequate planning, development, and engineering. There is no reason that future development repeat the mistakes of the past. There will be more development in Maine and communities must take steps to maintain and improve factors in Tables 1-4 to minimize the impact of future development in order to maintain water quality and prevent more impairments. Table 9 summarizes watershed management priorities for streams that attain biological criteria.

For streams that are already impaired, restoration does **not** necessarily mean ripping up large areas of IC. It is usually not practical nor socially desireable to remove lots of existing buildings and infrastructure. Municipalties can potentially improve water quality, however, by opportunisitically removing or relocating patches of IC or infrastructure that is antiquated or underutilized, especially if it is located near the stream, riparian corridor, or flood plains. In most circumstances, restoration will involve retrofitting existing infrastructure and improving the condition of factors in Tables 1-4 to improve water quality (Table 9). For example, redesigning stormwater infrastructure so the pipes do not directly discharge into streams can improve habitat quality and reduce flood severity, stream bank erosion, and the amount of pollutants reaching a stream [62]. A comparison of streams with similar watershed % IC showed that streams with less IC directly linked to streams through stormwater pipes had better water quality and aquatic communities than streams with more stormwater pipes conveying stormwater directly to the streams [63]. Reducing non-point source pollution and application of salt in a stream watershed can reduce nutrient and pollutant concentrations and improve macroinvertebrate community condition [64]. Protecting and restoring riparian buffers can improve water quality and ecological condition of urban streams [65]. Adding large woody debris to streams with sand-gravel substrate can increase macroinvertebrate abundance and diversity [15]. The effectiveness of restoring riparian forests and large woody debris may be limited, however, if other effects of intense urbanization and hydrologic alteration are not addressed [66, 67]. Restoration projects are more likely to succeed if there is a coordinated effort to target multiple stressors throughout the watershed. Since urban streams are often damaged by a variety of stressors, a key first step in restoration is to attempt to identify the factors that are contributing to the impairment and prioritize restoration on those factors based on complexity, cost, and expected benefits to water quality. Another key step is to identify the factors that remain in good condition and develop plans to maintain and improve those factors.



A) 1 square = 900 m^2

The squares overlap IC and vegetated areas, such as middle red box

Has trouble with small patches of vegetation or IC, such as left red box

B) 1 square = 25 m^2

Incorrectly identified most of the vegetation in right and left red boxes

Incorrectly identified most of the parking lot in the middle red box

C) 1 square = 1 m^2

Correctly identified vegetation in left and right boxes.

Correctly identified IC in middle red box

Figure 13. Comparison of resolution of three IC spatial data layers: A) 2001 National Land Cover Dataset (NLCD) with 30 m resoultion, B) 2004 Maine Land Cover Dataset (MLCD) data with 5 m resolution, and C) 2004 1 m data used in this study. *For A, each square has a % IC estimate from 0-100% represented with a color gradient from yellow to dark brown. The blue squares in B and C indicate IC. Red boxes on each picture define areas for comparison. Note the dramatic size difference of square sizes from A to C.*

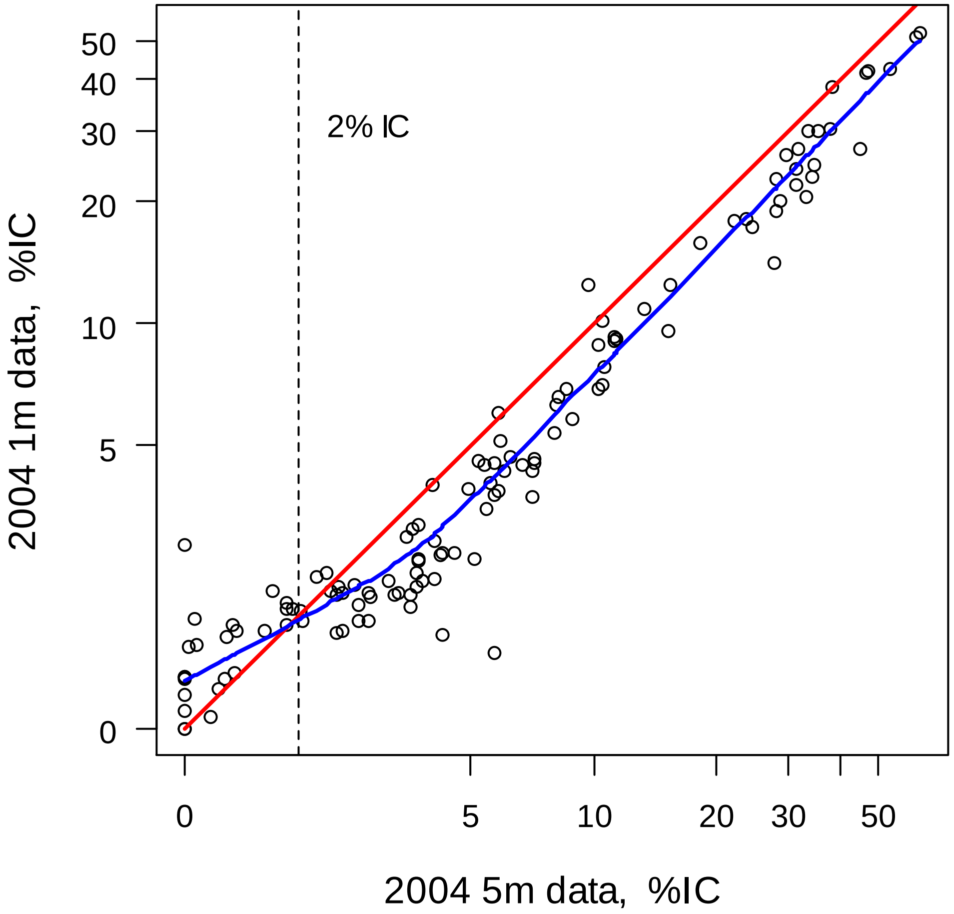


Figure 14. Comparison of % IC estimates from 2004 1 m data and 2004 5 m Maine Land Cover Dataset (MLCD) data. ($\log_{10}$ scale) *Th red diagonal line represents the 1:1 line where the two variables would equal each other. The blue curve represents the trend (locally-weighted regression line). The red and blue lines cross at 2% IC. Compared to the 1m data, the 5m data tends to underestimate watershed %IC when <2% and overestimate %IC when >2%.*

Table 9. Watershed management priorities given relative to the amount of IC in a stream's watershed and whether or not a stream attains biological criteria.

	Low % IC	% IC within transition range	High % IC
Attains biological criteria	• Maintain and improve favorable condition of factors in Tables 1-4 • Use best management practices to minimize impact of new development and IC	• Maintain and improve favorable condition of factors in Tables 1-4 • Use best management practices to minimize impact of new development and IC	• Identify factors that could be mitigating effects of IC • Target resources to protect and maintain mitigating factors • Use best management practices to minimize impact of new development and IC
Does not attain biological criteria	• Potentially not an IC stressor • Identify and target resources at potential sources of impairment • Use best management practices to minimize impact of new development and IC	• Determine if impairment was caused by IC and/or other stressor • Target resources at improving factors in Tables 1-4 • Use best management practices to minimize impact of new development and IC	• Stream is likely to be damaged by IC and multiple stressors • Retrofit storm drains, detention ponds, and other infrastructure to reduce impact to stream • Determine if groundwater contamination is an issue • Improve condition of factors in Tables 1-4, such as riparian corridor, flood plain, and channel condition • Use best management practices to minimize impact of new development and IC

VI. References

1. Schueler, T., *The importance of imperviousness.* Watershed Protection Techniques, 1994. **1**(3): p. 100-111.
2. Paul, M.J. and J.L. Meyer, *Streams in the urban landscape.* Annual Review of Ecology and Systematics, 2001. **32**: p. 333-365.
3. Center for Watershed Protection, *Impacts of Impervious Cover on Aquatic Systems*. 2003: Ellicott City, MD. Available from: clear.uconn.edu/projects/TMDL/library/papers/Schueler_2003.pdf.
4. Morse, C.C., A.D. Huryn, and C. Cronan, *Impervious surface area as a predictor of the effects of urbanization on stream insect communities in Maine, USA.* Environmental Monitoring and Assessment, 2003. **89**(1): p. 95-127.
5. Smucker, N.J., N.E. Detenbeck, and A.C. Morrison, *Diatom responses to watershed development and potential moderating effects of near-stream forest and wetland cover.* Freshwater Science, 2013. **32**(1): p. 230-249.
6. Morley, S.A. and J.R. Karr, *Assessing and restoring the health of urban streams in the Puget Sound basin.* Conservation Biology, 2002. **16**(6): p. 1498-1509.
7. Wang, L., et al., *Influences of watershed land use on habitat quality and biotic integrity of Wisconsin streams.* Fisheries, 1997. **22**: p. 6-12.
8. Danielson, T.J., et al., *Algal bioassessment metrics for wadeable streams and rivers of Maine, USA.* Journal of the North American Benthological Society, 2011. **30**(4): p. 1033-1048.
9. Baker, M.E. and R.S. King, *A new method for detecting and interpreting biodiversity and ecological community thresholds.* Methods in Ecology and Evolution, 2010. **9999**(9999).
10. Morgan, R.P. and S.F. Cushman, *Urbanization Effects on Stream Fish Assemblages in Maryland, USA.* Journal of the North American Benthological Society, 2005. **24**(3): p. 643-655.
11. Horwitz, R.J., et al., *Effects of riparian vegetation and watershed urbanization on fishes in streams of the mid-Atlantic piedmont (USA).* Journal of the American Water Resources Association, 2008. **44**(3): p. 724-741.
12. Walsh, C.J., et al., *The Urban Stream Syndrome: Current Knowledge and the Search for a Cure.* Journal of the North American Benthological Society, 2005. **24**(3): p. 706-723.
13. Meyer, J.L., M.J. Paul, and W.K. Taulbee, *Stream Ecosystem Function in Urbanizing Landscapes.* Journal of the North American Benthological Society, 2005. **24**(3): p. 602-612.
14. Vannote, R.L., et al., *River continuum concept.* Canadian Journal of Fisheries and Aquatic Sciences, 1980. **37**(1): p. 130-137.
15. Hrodey, P.J., B.J. Kalb, and T.M. Sutton, *Macroinvertebrate community response to large-woody debris additions in small warmwater streams.* Hydrobiologia, 2008. **605**: p. 193-207.
16. Langford, T.E.L., J. Langford, and S.J. Hawkins, *Conflicting effects of woody debris on stream fish populations: implications for management.* Freshwater Biology, 2012. **57**(5): p. 1096-1111.
17. Ogren, S.A. and D.K. King, *The effect of large woody debris on macroinvertebrate communities and epilithon detritus composition in a channelized headwater stream.* Journal of Freshwater Ecology, 2008. **23**(1): p. 65-77.

18. Ranalli, A.J. and D.L. Macalady, *The importance of the riparian zone and in-stream processes in nitrate attenuation in undisturbed and agricultural watersheds - A review of the scientific literature.* Journal of Hydrology, 2010. **389**(3-4): p. 406-415.
19. Poff, N.L., *Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology.* J. N. Am. Benthol. Soc., 1997. **16**(2): p. 391-409.
20. Wenger, S.J., et al., *Twenty-six key research questions in urban stream ecology: an assessment of the state of the science.* Journal of the North American Benthological Society, 2009. **28**(4): p. 1080-1098.
21. Elmore, A.J. and S.S. Kaushal, *Disappearing headwaters: patterns of stream burial due to urbanization.* Frontiers in Ecology and the Environment, 2008. **6**(6): p. 308-312.
22. Roth, N.E., J.D. Allan, and D.L. Erickson, *Landscape influences on stream biotic integrity assessed at multiple spatial scales.* Landscape Ecology, 1996. **11**: p. 141-156.
23. Alberti, M., et al., *The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins.* Landscape and Urban Planning, 2007. **80**(4): p. 345-361.
24. Blakely, T.J. and J.S. Harding, *Longitudinal patterns in benthic communities in an urban stream under restoration.* New Zealand Journal of Marine and Freshwater Research, 2005. **39**(1): p. 17-28.
25. Gangloff, M.M., *Taxonomic and ecological tradeoffs associated with small dam removals.* Aquatic Conservation-Marine and Freshwater Ecosystems, 2013. **23**(4): p. 475-480.
26. Blakely, T.J., et al., *Barriers to the recovery of aquatic insect communities in urban streams.* Freshwater Biology, 2006. **51**(9): p. 1634-1645.
27. Rosgen, D.L., *A classification of natural rivers.* Catena, 1994. **22**(3): p. 169-199.
28. Roy, J.W. and G. Bickerton, *Proactive screening approach for detecting groundwater contaminants along urban streams at the reach-scale.* Environmental Science & Technology, 2010. **44**(16): p. 6088-6094.
29. Roy, J.W. and G. Bickerton, *Toxic groundwater contaminants: An overlooked contributor to urban stream syndrome?* Environmental Science & Technology, 2012. **46**(2): p. 729-736.
30. Corsi, S.R., et al., *A Fresh Look at Road Salt: Aquatic Toxicity and Water-Quality Impacts on Local, Regional, and National Scales.* Environmental Science & Technology, 2010. **44**(19): p. 7376-7382.
31. Allert, A.L., C.L. Cole-Neal, and J.F. Fairchild, *Toxicity of Chloride Under Winter Low-Flow Conditions in an Urban Watershed in Central Missouri, USA.* Bulletin of Environmental Contamination and Toxicology, 2012. **89**(2): p. 296-301.
32. Canedo-Arguelles, M., et al., *Response of stream invertebrates to short-term salinization: A mesocosm approach.* Environmental Pollution, 2012. **166**: p. 144-151.
33. Daley, M.L., J.D. Potter, and W.H. McDowell, *Salinization of urbanizing New Hampshire streams and groundwater: effects of road salt and hydrologic variability.* Journal of the North American Benthological Society, 2009. **28**(4): p. 929-940.
34. Gillis, P.L., *Assessing the toxicity of sodium chloride to the glochidia of freshwater mussels: Implications for salinization of surface waters.* Environmental Pollution, 2011. **159**(6): p. 1702-1708.

35. Morgan, R.P., et al., *Stream Conductivity: Relationships to Land Use, Chloride, and Fishes in Maryland Streams.* North American Journal of Fisheries Management, 2007. **32**(5): p. 941-952.
36. Pandolfo, T.J., et al., *Acute effects of road salts and associated cyanide compounds on the early life stages of the unionid mussel Villosa iris.* Environmental Toxicology and Chemistry, 2012. **31**(8): p. 1801-1806.
37. Todd, A.K. and M.G. Kaltenecker, *Warm season chloride concentrations in stream habitats of freshwater mussel species at risk.* Environmental Pollution, 2012. **171**: p. 199-206.
38. Harte, P.T. and P.R. Trowbridge, *Mapping of road-salt-contaminated groundwater discharge and estimation of chloride load to a small stream in southern New Hampshire, USA.* Hydrological Processes, 2010. **24**(17): p. 2349-2368.
39. Trowbridge, P.R., et al., *Relating road salt to exceedances of the water quality standard for chloride in New Hampshire streams.* Environmental Science & Technology, 2010. **44**(13): p. 4903-4909.
40. Porter-Goff, E.R., P.C. Frost, and M.A. Xenopoulos, *Changes in riverine benthic diatom community structure along a chloride gradient.* Ecological Indicators, 2013. **32**: p. 97-106.
41. Vander Laan, J.J., et al., *Linking land use, in-stream stressors, and biological condition to infer causes of regional ecological impairment in streams.* Freshwater Science, 2013. **32**(3): p. 801-820.
42. USEPA, *A field-based aquatic life benchmark for conductivity in central Appalachian streams. EPA/600/R-10/023*. 2011, Office of Research and Development, National Center for Environmental Assessment, US Environmental Protection Agency, Washington, DC: Washington, DC.
43. Bernhardt, E.S., et al., *How many ountains can we mine? Assessing the regional degradation of Central Appalachian rivers by surface coal mining.* Environmental Science & Technology, 2012. **46**(15): p. 8115-8122.
44. Meidel, S. and M. Evers, *Birch Stream Total Maximum Daily Load (TMDL). DEPLW0715*. 2007, Maine Department of Environmental Protection: Augusta, ME.
45. Meidel, S. and MDEP, *Trout Brook Total Maximum Daily Load (TMDL). DEPLW0714*. 2003, Maine Department of Environmental Protection: Augusta, ME.
46. Meidel, S. and MDEP, *Barberry Creek Total Maximum Daily Load (TMDL). DEPLW0712*. 2003, Maine Department of Environmental Protection: Augusta, ME.
47. R Development Core Team, *R: A Language and Environment for Statistical Computing*. 2008, R Foundation for Statistical Computing: Vienna, Austria.
48. *An editor for R language and environment statistical computing.* . Tinn-R Development Team 2004, http://www.sciviews.org/Tinn-R/ and http://sourceforge.net/projects/tinn-r. .
49. Davies, S.P. and L. Tsomides, *Methods for Biological Sampling of Maine's Rivers and Streams*. 2002, Maine Department of Environmental Protection: Augusta, ME.
50. Morse, C. and S. Kahl, *Measuring the Impact of Development on Maine Surface Waters*. 2003, Senator George J. Mitchell Center for Environmental and Watershed Research, University of Maine: Orono, ME.
51. Wang, L. and P. Kanehl, *Influences of watershed urbanization and instream habitat on macroinvertebrates in cold water streams.* Journal of the American Water Resources Association, 2003. **39**(5): p. 1181-1196.

52. Roy, A.H., et al., *Stream macroinvertebrate response to catchment urbanisation (Georgia, USA).* Freshwater Biology, 2003. **48**(2): p. 329-346.
53. King, R.S., et al., *How novel is too novel? Stream community thresholds at exceptionally low levels of catchment urbanization.* Ecological Applications, 2011. **21**(5): p. 1659-1678.
54. van Dam, H., A. Mertens, and J. Sinkeldam, *A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands.* Netherlands Journal of Aquatic Ecology, 1994. **28**(1): p. 117-133.
55. Wang, Y.K., R.J. Stevenson, and L. Metzmeier, *Development and evaluation of a diatom-based Index of Biotic Integrity for the Interior Plateau Ecoregion, USA.* Journal of the North American Benthological Society, 2005. **24**(4): p. 990-1008.
56. Fore, L.S. and C. Grafe, *Using diatoms to assess the biological condition of large rivers in Idaho (USA).* Freshwater Biology, 2002. **47**(10): p. 2015-2037.
57. Bahls, L.L., *Periphyton Bioassessment Methods for Montana Streams*. 1993, Montana Water Quality Bureau, Department of Health and Environmental Sciences: Helena, Montana. p. 23.
58. Qian, S.S., R.S. King, and C.J. Richardson, *Two statistical methods for the detection of environmental thresholds.* Ecological Modelling, 2003. **166**(1-2): p. 87-97.
59. King, R.S. and M.E. Baker, *Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients.* Journal of the North American Benthological Society, 2010. **29**(3): p. 998-1008.
60. MDEP, *Maine Impervious Cover Total Maximum Daily Load Assessment (TMDL) for Impaired Streams (DEPLW-1239)*. 2012, Maine Department of Environmental Protection: Augusta, ME.
61. Smucker, N.J., J.L. DeForest, and M.L. Vis, *Different methods and storage duration affect measurements of epilithic extracellular enzyme activities in lotic biofilms.* Hydrobiologia, 2009. **636**(1): p. 153-162.
62. Walsh, C.J., T.D. Fletcher, and A.R. Ladson, *Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream.* Journal of the North American Benthological Society, 2005. **24**(3): p. 690-705.
63. Walsh, C.J., T.D. Fletcher, and M.J. Burns, *Urban stormwater runoff: A new class of environmental flow problem.* Plos One, 2012. **7**(9).
64. Johnson, L.B. and G.E. Host, *Recent developments in landscape approaches for the study of aquatic ecosystems.* Journal of the North American Benthological Society, 2013. **29**(1): p. 41-66.
65. Thompson, R. and S. Parkinson, *Assessing the local effects of riparian restoration on urban streams.* New Zealand Journal of Marine and Freshwater Research, 2011. **45**(4): p. 625-636.
66. Roy, A.H., et al., *Importance of riparian forests in urban catchments contingent on sediment and hydrologic regimes.* Environmental Management, 2006. **37**(4): p. 523-539.
67. Larson, M.G., D.B. Booth, and S.A. Morley, *Effectiveness of large woody debris in stream rehabilitation projects in urban basins.* Ecological Engineering, 2001. **18**(2): p. 211-226.

Appendix 1. Macroinvertebrate z- indicator taxa, including the taxonomic group, taxon name, taxon code used in figures, taxon frequency (n), % IC change point, strength of the change point (z), and percentiles (%tile) of the change points of 500 bootstrap permutations to estimate uncertainty of the change points.

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
STONEFLY	Amphinemura	Amphinem	12	0.32	22.58	0.31	0.31	0.32	0.32	0.32
STONEFLY	Capniidae	CapniidF	8	0.33	5.54	0.11	0.11	0.33	3.71	3.74
STONEFLY	Leuctra	Leuctra	53	13.38	3.28	5.97	5.97	13.38	20.73	20.76
STONEFLY	Pteronarcys	Pteronar	23	1.01	8.66	0.41	0.43	1.05	2.89	2.89
STONEFLY	Perlodidae	PerlodiF	45	3.61	5.27	0.60	0.68	3.61	11.68	20.73
STONEFLY	Isoperla	Isoperla	18	1.11	5.82	0.23	0.23	1.11	3.53	3.56
STONEFLY	Chloroperlidae	ChloropF	14	0.42	5.74	0.31	0.31	0.42	2.87	6.14
STONEFLY	Sweltsa	Sweltsa	25	11.68	2.86	0.26	0.28	5.97	11.68	13.10
STONEFLY	Perlidae	PerlidaF	22	1.79	4.55	1.36	1.53	1.83	8.70	8.82
STONEFLY	Acroneuria	Acroneur	49	3.77	5.43	2.28	2.34	3.77	13.38	13.38
STONEFLY	Agnetina	Agnetina	32	3.64	6.67	1.53	1.58	3.64	3.64	3.68
DRAGONFLY	Gomphidae	GomphidF	21	15.52	2.52	1.00	1.58	1.98	15.52	16.51
MAYFLY	Baetidae	BaetidaF	67	11.35	3.45	6.78	6.85	11.35	20.73	20.76
MAYFLY	Baetis	Baetis	80	11.68	4.24	5.97	6.55	11.35	22.61	23.29
MAYFLY	Acerpenna	Acerpenn	75	11.35	5.75	6.85	8.82	11.35	11.35	11.63
MAYFLY	Plauditus	Plauditu	23	8.70	3.32	3.34	4.60	8.70	8.82	8.89
MAYFLY	Heptageniidae	HeptageF	65	10.32	4.97	5.97	5.97	8.43	10.38	10.38
MAYFLY	Epeorus	Epeorus	35	2.14	6.85	0.92	1.04	2.09	3.51	3.52
MAYFLY	Heptagenia	Heptagen	10	3.50	3.45	0.13	0.28	1.04	3.51	3.52
MAYFLY	Leucrocuta	Leucrocu	47	3.51	8.26	2.94	3.39	3.52	3.64	6.85
MAYFLY	Maccaffertium	Maccaffe	91	10.32	7.51	7.67	8.43	10.32	10.38	10.38
MAYFLY	Isonychia	Isonychi	19	4.60	2.79	1.54	1.79	4.60	8.82	8.82
MAYFLY	Leptophlebiidae	LeptophF	68	13.38	4.25	6.78	6.85	10.38	20.73	20.76
MAYFLY	Habrophlebia	Habrophl	10	1.14	4.41	0.64	0.84	1.13	1.15	10.32

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
MAYFLY	Paraleptophlebia	Paralept	38	10.32	2.78	0.85	2.35	8.62	18.72	18.84
MAYFLY	Ephemerellidae	EphemllF	52	6.85	4.48	2.94	4.60	7.02	10.38	10.38
MAYFLY	Ephemerella	Ephemere	48	1.79	8.67	1.74	1.78	1.80	10.38	11.68
MAYFLY	Eurylophella	Euryloph	60	10.32	3.76	1.15	6.13	10.32	13.38	14.10
CADDISFLY	Dolophilodes	Dolophil	39	11.68	3.63	3.53	3.67	10.38	13.10	13.14
CADDISFLY	Chimarra	Chimarra	41	11.35	2.89	0.60	5.06	11.35	19.11	24.85
CADDISFLY	Neureclipsis	Neurecli	30	8.70	3.99	2.42	3.13	7.18	8.82	8.89
CADDISFLY	Polycentropus	Polycent	61	11.35	4.58	10.20	10.27	11.35	11.37	11.63
CADDISFLY	Hydropsychidae	HydropsF	83	20.73	3.18	0.21	13.38	20.73	34.19	40.80
CADDISFLY	Rhyacophila	Rhyacoph	86	11.68	5.63	6.78	6.85	11.68	13.82	20.73
CADDISFLY	Glossosoma	Glossoso	37	11.40	3.64	3.50	3.64	8.26	11.68	13.10
CADDISFLY	Brachycentrus	Brachyct	26	2.29	7.11	1.01	1.04	2.16	4.60	4.83
CADDISFLY	Micrasema	Micrasem	16	5.06	3.24	1.01	3.13	5.06	5.07	5.35
CADDISFLY	Neophylax	Neophyla	11	0.31	15.58	0.31	0.31	0.32	0.59	0.62
CADDISFLY	Lepidostoma	Lepidost	57	6.14	5.07	0.60	4.31	6.14	7.12	13.38
CADDISFLY	Psilotreta	Psilotre	49	13.38	3.45	6.04	6.14	10.32	14.10	15.09
CADDISFLY	Ceraclea	Ceraclea	11	2.42	4.41	1.22	1.31	2.42	2.46	2.58
FLY: MIDGE	Rheopelopia	Rheopelo	34	9.24	3.26	2.87	3.51	8.70	10.27	18.87
FLY: MIDGE	Diplocladius	Diplocla	11	0.32	7.12	0.12	0.31	0.31	0.32	11.35
FLY: MIDGE	Rheocricotopus	Rheocric	64	20.73	3.22	4.84	5.58	11.88	20.76	21.34
FLY: MIDGE	Tvetenia	Tvetenia	101	20.73	3.53	7.67	16.51	20.73	40.80	41.26
FLY: MIDGE	Stempellinella	Stempell	52	13.38	3.93	0.79	10.19	13.38	18.73	18.84
FLY: WATERSNIPE	Atherix	Atherix	50	6.85	4.97	6.68	6.78	7.02	10.32	10.38
BEETLE	Psephenus	Psephenu	46	13.38	4.01	0.70	2.33	11.35	14.10	15.09
BEETLE	Optioservus	Optioser	43	13.38	3.67	8.70	10.32	13.38	14.10	15.09
BEETLE	Promoresia	Promores	78	10.32	5.42	3.53	5.06	8.70	13.45	18.72

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
MITE	Lebertia	Lebertia	16	0.33	6.62	0.10	0.13	0.32	19.23	20.73

Appendix 2. Macroinvertebrate z+ indicator taxa, including the taxonomic group, taxon name, taxon code used in figures, taxon frequency (n), % IC change point, strength of the change point (z), and percentiles (%tile) of the change points of 500 bootstrap permutations to estimate uncertainty of the change points.

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
PLANARIA	Planariidae	PlanariF	15	1.26	3.67	0.93	0.93	1.74	2.89	5.59
RIBBON WORM	Prostoma	Prostoma	11	3.64	5.55	1.15	2.27	3.64	25.55	25.55
WORM	Lumbriculidae	LumbrclF	6	5.06	5.38	2.42	2.42	5.06	27.28	38.18
WORM	Eclipidrilus	Eclipidr	6	39.17	13.80	20.33	20.72	30.78	41.19	41.26
WORM	Enchytraeidae	EnchytrF	25	11.35	7.87	2.63	4.83	11.35	26.89	27.28
WORM	Naididae	NaididaF	27	11.35	19.02	10.27	10.38	15.52	19.12	19.48
WORM	Nais	Nais	51	0.60	3.81	0.58	0.59	0.69	1.87	2.63
WORM	Lumbricidae	LumbricF	18	11.35	10.49	7.83	8.00	11.40	16.51	27.54
LEECH	Erpobdellidae	ErpobdeF	7	22.61	18.37	0.13	5.29	22.61	39.17	39.17
ISOPOD	Caecidotea	Caecidot	20	5.29	10.95	4.52	5.07	7.67	19.11	19.23
CRAYFISH	Orconectes	Orconect	18	0.70	3.11	0.69	0.70	1.00	1.08	1.27
DRAGONFLY	Aeshna	Aeshna	11	22.61	10.11	1.18	14.10	22.61	40.87	41.26
MAYFLY	Caenis	Caenis	28	0.35	2.70	0.35	0.35	0.51	0.70	1.25
CADDISFLY	Phylocentropus	Phylocen	12	2.42	5.06	2.21	2.30	2.46	33.08	34.19
CADDISFLY	Ptilostomis	Ptilosto	7	5.29	5.95	2.42	2.42	13.10	25.55	25.55
CADDISFLY	Limnephilus	Limnephi	17	11.35	11.08	2.42	5.29	11.40	30.93	33.08
FISHFLY	Sialis	Sialis	30	2.42	5.17	0.77	1.28	2.42	11.35	12.12
FLY: CRANE	Limnophila	Limnophi	9	19.23	6.21	1.52	1.54	19.23	19.24	22.00
FLY: MIDGE	Ablabesmyia	Ablabesm	38	0.35	2.78	0.35	0.35	0.70	6.43	18.45

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
FLY: MIDGE	Conchapelopia	Conchape	44	0.37	2.81	0.36	0.36	0.54	2.76	4.02
FLY: MIDGE	Meropelopia	Meropelo	32	15.52	6.31	0.58	2.42	14.10	26.80	28.80
FLY: MIDGE	Natarsia	Natarsia	28	11.40	5.60	0.80	1.54	11.40	29.96	32.26
FLY: MIDGE	Procladius	Procladi	14	0.81	2.28	0.33	0.79	3.39	25.55	25.55
FLY: MIDGE	Prodiamesa	Prodiame	14	11.35	15.41	10.27	10.38	11.40	18.87	19.48
FLY: MIDGE	Parakiefferiella	Parakief	27	0.73	3.09	0.33	0.51	0.73	13.38	15.48
FLY: MIDGE	Cladotanytarsus	Cladotan	14	3.53	3.15	0.79	0.79	3.52	4.06	5.59
FLY: MIDGE	Paratanytarsus	Paratany	31	13.38	6.42	0.70	1.11	13.38	22.70	24.85
FLY: MIDGE	Chironomus	Chironom	10	24.85	11.39	10.38	11.35	24.85	40.73	41.19
FLY: MIDGE	Cryptochironomus	Cryptoch	13	8.62	7.67	2.81	4.84	8.62	23.12	40.87
FLY: MIDGE	Dicrotendipes	Dicroten	24	13.38	5.19	0.74	0.90	13.10	15.09	22.61
FLY: MIDGE	Paratendipes	Paratend	24	7.67	6.48	1.19	2.30	7.67	11.35	24.85
FLY: MIDGE	Phaenopsectra	Phaenops	39	0.81	4.15	0.70	0.70	0.92	3.31	3.68
FLY: MIDGE	Stictochironomus	Stictoch	9	11.35	10.41	7.83	8.00	11.40	18.87	19.11
FLY: MIDGE	Rheosmittia	Rheosmit	6	3.48	5.35	3.39	3.41	3.51	34.19	36.49
FLY: HORSE AND DEER	Chrysops	Chrysops	18	2.42	4.32	0.33	1.54	3.38	11.40	13.38
FLY: AQUATIC DANCE	Chelifera	Chelifer	12	3.48	2.92	0.57	0.58	8.70	40.87	41.19
SNAIL	Physa	Physa	24	2.89	5.79	1.00	1.11	3.74	15.52	16.51
SNAIL	Physella	Physella	15	1.19	2.42	0.53	0.53	2.82	40.80	41.26
CLAM	Sphaeriidae	SphaeriF	37	0.70	3.28	0.32	0.32	0.70	8.87	10.21
CLAM	Pisidium	Pisidium	35	1.13	4.12	0.33	0.33	1.22	3.39	3.39

Appendix 3. Algal z- indicator, including the taxonomic group, taxon name, taxon code used in figures, taxon frequency (n), % IC change point, strength of the change point (z), and percentiles (%tile) of the change points of 500 bootstrap permutations to estimate uncertainty of the change points.

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
CENTRIC DIATOM	Aulacoseira ambigua	AUambigu	8	1.17	4.64	0.00	0.94	1.17	2.68	2.77
PENNATE DIATOM	Brachysira brebissonii	BRbrebis	12	1.09	5.01	0.01	0.76	1.09	2.68	2.77
PENNATE DIATOM	Chamaepinnularia mediocris	CKmedioc	7	0.00	5.72	0.00	0.00	0.18	0.70	10.59
PENNATE DIATOM	Cymbella delicatula	CMdelcat	11	1.36	6.99	1.08	1.14	1.36	1.37	1.38
PENNATE DIATOM	Diatoma mesodon	DAmesodo	16	0.87	6.62	0.32	0.32	0.87	1.90	9.56
PENNATE DIATOM	Eunotia exigua	EUexigua	29	1.09	8.08	0.32	0.52	0.97	1.99	2.14
PENNATE DIATOM	Eunotia implicata	EUimplic	34	10.59	3.01	0.47	1.17	10.41	10.79	11.54
PENNATE DIATOM	Eunotia incisa	EUincisa	37	10.59	4.19	3.26	3.56	8.56	11.64	20.76
PENNATE DIATOM	Eunotia muscicola var. tridentula	EUmustri	11	0.28	12.24	0.00	0.04	0.17	0.87	0.87
PENNATE DIATOM	Eunotia pectinalis	EUpectin	8	1.09	4.67	0.00	0.14	1.09	1.62	1.65
PENNATE DIATOM	Fragilariforma virescens	FAviresc	11	1.33	6.66	0.00	0.18	1.03	1.33	1.35
PENNATE DIATOM	Frustulia crassinervia	FScrassi	16	8.07	3.02	0.01	0.18	4.80	8.31	8.56
PENNATE DIATOM	Navicula angusta	NAangust	8	0.00	31.19	0.00	0.00	0.01	0.87	0.89
PENNATE DIATOM	Navicula notha	NAnotha	19	11.49	2.98	0.05	0.94	10.66	12.24	12.34
PENNATE DIATOM	Pinnularia subcapitata	PIsubcap	10	1.33	5.95	0.00	0.78	1.09	1.35	1.35
PENNATE DIATOM	Psammothidium grischunum fo. daonensis	PSgridao	10	0.83	6.09	0.00	0.32	0.83	1.04	1.07
PENNATE DIATOM	Psammothidium marginulatum	PSmargin	6	0.01	11.20	0.00	0.00	0.00	0.87	1.90
PENNATE DIATOM	Rossithidium linearis	RMlinear	11	1.41	3.02	1.11	1.14	1.43	2.88	6.89
PENNATE DIATOM	Stauroneis anceps	SSanceps	6	1.14	4.92	0.18	0.54	1.14	1.15	1.18
PENNATE DIATOM	Staurosirella pinnata	SLpinnat	18	4.80	4.17	1.43	2.00	3.29	5.53	6.13
PENNATE DIATOM	Tabellaria flocculosa	TAfloccu	51	11.49	5.18	1.20	1.21	11.49	12.24	12.34

Appendix 4. Algal z+ indicator taxa, including the taxonomic group, taxon name, taxon code used in figures, taxon frequency (n), % IC change point, strength of the change point (z), and percentiles (%tile) of the change points of 500 bootstrap permutations to estimate uncertainty of the change points.

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
CENTRIC DIATOM	Cyclotella meneghiniana	CYmenegh	28	1.93	6.78	0.87	0.87	1.86	2.83	3.06
CENTRIC DIATOM	Melosira varians	MEvarian	26	2.91	5.33	0.32	0.75	2.22	3.14	3.56
PENNATE DIATOM	Amphora pediculus	AMpedcls	20	10.59	10.23	2.83	3.58	10.59	17.63	17.81
PENNATE DIATOM	Caloneis bacillum	CAbacill	16	2.49	5.08	0.76	0.76	2.49	11.49	11.49
PENNATE DIATOM	Cocconeis placentula var. euglypta	CCplaeug	16	1.02	3.24	0.29	1.02	1.36	3.23	19.04
PENNATE DIATOM	Diatoma moniliformis	DAmonili	14	0.98	2.46	0.95	0.97	1.21	4.65	19.09
PENNATE DIATOM	Gomphonema kobayasii	GOkobaya	23	1.33	6.32	0.95	0.98	1.33	2.83	9.24
PENNATE DIATOM	Navicula antonii	NAanton	10	1.39	4.09	1.36	1.37	1.39	3.44	3.52
PENNATE DIATOM	Navicula germainii	NAgermai	6	2.22	4.42	2.13	2.15	2.22	8.56	9.38
PENNATE DIATOM	Navicula gregaria	NAgregar	36	2.91	11.00	1.28	1.86	2.91	3.21	3.21
PENNATE DIATOM	Navicula lanceolata	NAlanceo	20	5.56	11.33	5.53	5.53	8.07	10.79	13.29
PENNATE DIATOM	Navicula menisculus	NAmenscl	7	2.83	3.56	1.25	1.28	2.83	8.89	10.59
PENNATE DIATOM	Navicula trivialis	NAtrivia	9	17.63	6.47	1.09	1.09	17.63	18.64	22.84
PENNATE DIATOM	Navicula veneta	NAveneta	9	8.89	4.51	0.76	1.37	8.89	20.76	25.86
PENNATE DIATOM	Nitzschia amphibia	NIamphib	13	15.21	6.35	1.37	3.52	15.21	25.86	27.16
PENNATE DIATOM	Nitzschia archibaldii	NIarchi	9	4.57	5.33	1.29	1.33	4.57	28.78	29.72
PENNATE DIATOM	Nitzschia dissipata	NIdissip	30	0.66	4.18	0.14	0.54	0.66	1.08	23.90
PENNATE DIATOM	Nitzschia frustulum	NIfrustu	22	0.49	3.13	0.44	0.45	0.91	1.26	4.57
PENNATE DIATOM	Nitzschia inconspicua	NIincons	15	9.38	11.32	3.58	3.64	9.38	22.61	23.26
PENNATE DIATOM	Nitzschia palea	NIpalea	37	0.14	2.77	0.12	0.12	0.40	1.05	1.09
PENNATE DIATOM	Nitzschia pusilla	NIpusill	7	26.08	11.78	2.83	2.91	22.13	28.78	28.78
PENNATE DIATOM	Nitzschia supralitorea	NIsupral	12	1.09	4.09	1.08	1.08	2.63	3.06	8.33
PENNATE DIATOM	Nitzschia tubicola	NItubico	11	13.29	9.58	1.47	4.57	13.29	17.63	17.81
PENNATE DIATOM	Planothidium frequentissimum	PLfreque	32	1.93	10.04	1.43	1.43	2.12	2.91	3.14

Group	Taxon	Code	n	Change point	z	5 %tile	10 %tile	Median	90 %tile	95 %tile
PENNATE DIATOM	Reimeria sinuata	REsinuat	44	0.83	3.74	0.00	0.00	0.83	2.49	2.83
PENNATE DIATOM	Rhoicosphenia abbreviata	ROabbrev	21	3.64	6.68	1.02	1.28	3.58	4.07	8.32
PENNATE DIATOM	Surirella angusta	SUangust	13	17.63	9.99	2.22	8.56	17.63	21.62	23.83
PENNATE DIATOM	Surirella brebissonii var. kuetzingii	SUbrekue	10	1.86	5.95	1.82	1.85	1.86	11.12	18.41
PENNATE DIATOM	Surirella minuta	SUminuta	11	3.14	8.87	3.14	3.14	8.07	19.09	19.11