Natural Drainage Systems
Pre-Project Monitoring on Pipers Creek

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Report of research to

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by

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Executive Summary

Relatively little scientific research or monitoring has occurred in the Pacific Northwest or elsewhere on the biological effectiveness of restoration efforts in heavily urbanized watersheds. With the overarching goal of improving ecological health of its urban creeks, the City of Seattle is testing innovative approaches to stormwater management. We report here on four years of pre-project monitoring data collected over 2006-2009 for one such technique: Natural Drainage Systems (NDS).

This low-impact development approach is designed to modify the quantity, quality, and timing of stormwater delivery to creeks and other water bodies. Seattle Public Utilities has proposed a large-scale NDS within the Pipers Creek basin of North Seattle that will treat approximately 60% of the Venema Creek sub-basin. The focus of NOAA's research effort has been to develop appropriate monitoring parameters and collect baseline data to evaluate the effectiveness of this major restoration action. Our selection of study parameters was guided by specific project goals and includes measures of physical habitat, contaminant loading, and in-stream biota.

We found that the biological health of Pipers Creek is poor compared to forested streams in the Puget Sound region, but comparable to other urban streams in the City of Seattle. The fish community is dominated by cutthroat trout *Oncorhynchus clarki*; scores for the benthic index of biological integrity (B-IBI) range from very poor to poor; and diatom assemblages are composed of a relatively high proportion of species tolerant of high nutrient levels, organic enrichment, and sedimentation.

Despite poor stream health, densities of cutthroat trout in three of our five study reaches were higher than many urban streams and approaching densities of cutthroat found in natural streams. This may be due to the migratory nature of cutthroat trout, as about half these fish were detected migrating from our study area to lower Piper Creek or Puget Sound.

Results from heavy metal sampling were inconsistent. Zinc concentrations in soil, black fly larvae, and mayfly nymphs collected from Pipers Creek study reaches were significantly higher than for forested streams. We did not detect any differences in copper concentrations between urban and non-urban streams.

We hypothesize that in-stream biological health will improve relative to current baseline conditions following Venema NDS implementation, with treated reaches beginning to more closely resemble forested conditions. Based on statistical power

analyses, we recommend that post-project monitoring focus on rate and taxonomic composition metrics rather than simple density measurements. Given the City of Seattle's considerable investment of restoration funds towards NDSs, it is critical that post-project data be collected so as to explicitly test these hypotheses.

Contents

Introduction

Urban streams are the unfortunate recipients of a diverse range of interacting stressors (Karr and Chu 2000). Chief among these is urban stormwater runoff, which not only washes fine sediments and contaminants into streams, but also greatly alters the natural hydrologic regime (DeGasperi et al. 2009). The term "Urban Stream Syndrome" was coined by ecologists to describe the depressing commonalities of urban streams worldwide—features which inevitably result in reduced biological health (Walsh et al. 2005). Too many symptoms of this syndrome are evident in watersheds across the Puget Sound region—from dry creek beds lacking groundwater recharge (Konrad and Booth 2002) to the phenomenon of coho pre-spawn mortality (Sandahl et al. 2007).

An unbalanced flow regime of rapid and frequent peak flow events coupled with inadequate groundwater recharge typically results from the replacement of natural soils and forest cover with impervious surfaces and a highly built-out artificial drainage network (Konrad and Booth 2002). Common physical stressors such as channelization and bank armoring further exacerbate the biological consequences of flow alteration via decreased floodplain complexity and connectivity (McBride and Booth 2005; Pess et al. 2005).

Traditional approaches attempting to correct these impacts have been criticized for treating symptoms rather than causes and for their narrow spatial scope (Morley and Karr 2002; Booth et al. 2004). The limited restoration monitoring conducted in the Pacific Northwest or elsewhere on urban watershed restoration efforts is not encouraging (Larson et al. 2001; Roni et al. 2002). In particular, stormwater detention ponds alone have proven inadequate to mitigate the effects of urban development (Booth et al. 2002). While it is unrealistic to think that any restoration approach will return streams in heavily urbanized landscapes to pre-development conditions, we can and must do better.

The City of Seattle has taken up this challenge, and over the last decade began developing an innovative stormwater management approach known as Natural Drainage Systems (NDS). This low-impact development technique aims to improve the quantity, quality, and timing of stormwater delivery to creeks and other water bodies. A major advantage of NDSs is that they are designed to address causes rather than only symptoms, and to do so by mimicking natural forested conditions. In this approach, city blocks (and in some cases, neighborhoods) are redesigned for improved stormwater infiltration and storage via bioswales that involve extensive use of native soils and plants (Kloss and Calarusse 2006). Impervious surfaces are also reduced via road narrowing and use of porous concrete and other pervious paving materials.

An NDS pilot project began in 2001 with the *Seattle Street-Edge Alternative* in North Seattle, and has recently been scaled up to larger areas such as the High Point redevelopment in West Seattle (Buranen 2010). Results of on-site monitoring conducted by the University of Washington for existing projects are promising. These researchers report substantial decrease in run-off from project areas and a reduction in many classes of contaminants between project inlets and outlets (Horner and Chapman 2007; Horner and Reiners 2009). Additional NDS benefits include re-greening of city neighborhoods, increased property values, and opportunities for community stewardship and public education.

Contingent upon funding, the next NDS is planned for the Venema Creek sub-basin of Pipers Creek in North Seattle (Figure 1). It will be the first such project to address the majority of stormwater runoff from a single drainage basin in the City of Seattle, and is designed to treat approximately 60% of the Venema Creek drainage basin.

Seattle Public Utilities' overarching goal in promoting NDS projects is to improve the health of creek biota by naturalizing hydrologic regime, reducing contaminant levels in stormwater runoff, decreasing sedimentation rates, and improving in-stream habitat (Table 1). While SPU has monitored other NDS projects and will monitor the completed Venema project for water quantity and quality, no monitoring of NDS project effectiveness has yet occurred within the stream itself.

Our two main research objectives were 1) to determine appropriate monitoring parameters for NDS in-stream monitoring, and 2) to establish baseline conditions prior to construction of the Venema NDS. Our primary focus in monitoring has been stream biota, as the health of the organisms residing in Pipers Creek is the ultimate test of restoration success. In addition to sampling fish, benthic invertebrates, and periphyton, we have been monitoring a suite of physical and chemical habitat parameters that are directly linked to NDS goals (Table 1). Based on this data collection, we report here our evaluation of present condition in Pipers Creek compared with those of other urban and forested streams in the region. Recommendations for post-project monitoring are also based on these data collections.

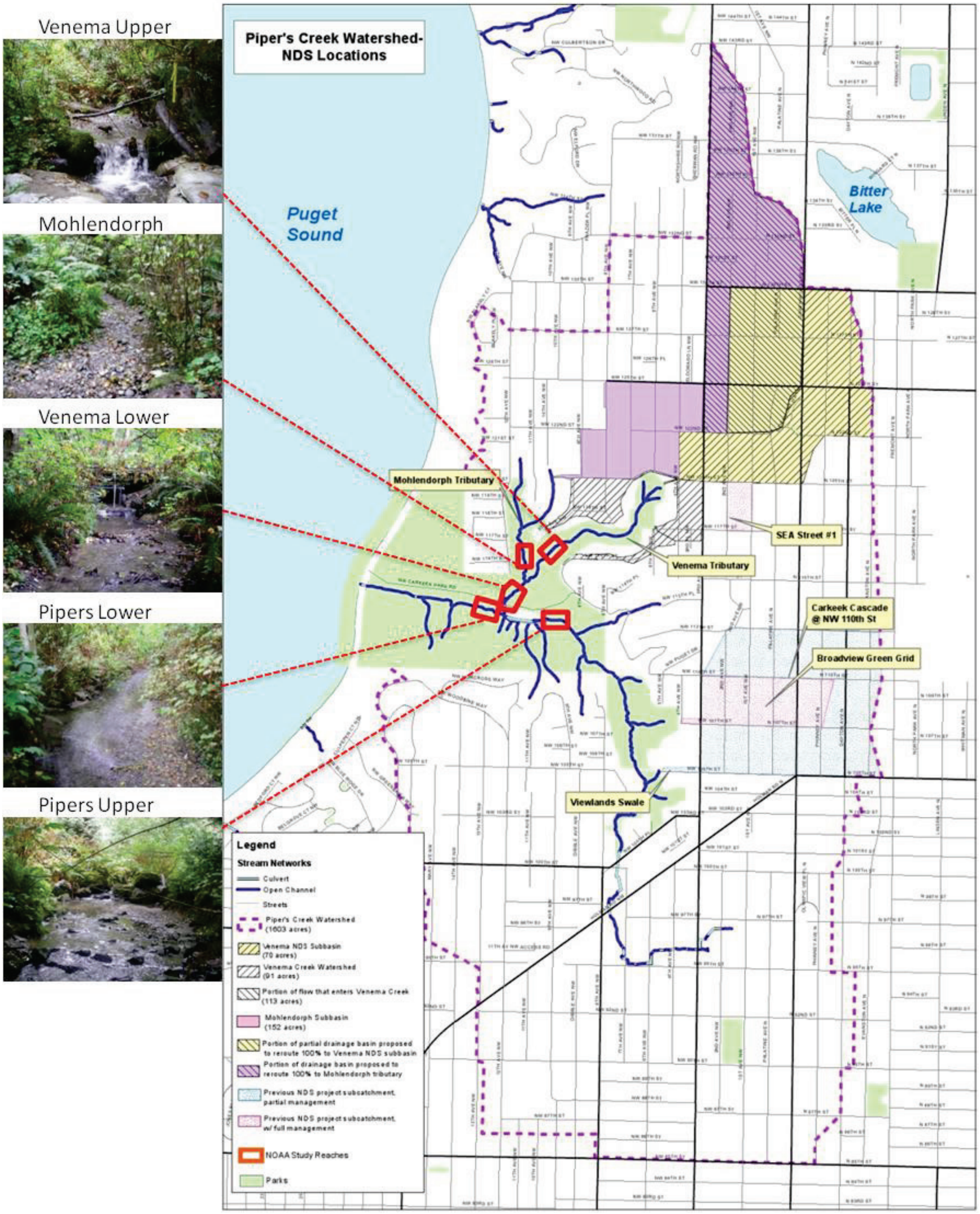

Figure 1. Map of the study region indicating locations of current and proposed natural drainage system projects within the Pipers Creek watershed. The five 50-m long NOAA study reaches are outlined in red. All photos were taken in September 2007 from the downstream end of the study reach, looking upstream.

Table 1. Goals of the Natural Drainage System project showing NOAA monitoring parameters, sampling protocols, and hypothesized response to drainage restoration. Details of specific parameters and associated sampling techniques are provided in the methodology section of this report.

Parameter	Sampling protocol	Hypothesized response to restoration
Naturalize hydrologic regime		
Rainfall and stream discharge	Flow and rain gauges maintained and monitored by Seattle Public Utilities	Increased stormwater retention will decrease overall stream "flashiness:" frequency and volume of peak flows will decrease and base flows will increase.
Decrease contaminant levels in urban run-off		
Zinc and copper	Chemical analysis of soil, periphyton, and benthic invertebrate samples	Increased retention and filtration of stormwater will improve water quality of runoff and result in lower concentrations of metals in surface soils, periphyton, and benthic invertebrates in Pipers Creek treatment reaches.
Improve habitat quality		
Channel morphology	Long-profile, cross-section, and habitat surveys	Decreased frequency and volume of peak flows will reduce channel incision rates, improve streambank condition, and result in a higher diversity of habitat types and water depths.
Reduce sedimentation		
Streambed substrate	Surface pebble counts and subsurface volumetric sampling	Decreased peak flows and greater filtration of stormwater will improve particle size heterogeneity, decrease proportion of fine sediments present, and lower overall embededdness of surface substrate.
Improve health of stream biota		
Periphyton	Ash-free dry mass and chlorophyll-*a* density; diatom taxonomic and functional diversity	Improved water quality, decreased fine sediment inputs, and attenuated flow regime will increase periphyton standing crop, improve diatom species diversity, and decrease the relative abundance of species tolerant of high levels of sedimentation and nutrient enrichment.
Benthic Invertebrates	Riffle sampling for total density, benthic index of biological integrity (B-IBI) and associated metrics	Decreased sedimentation, attenuated flow regime, improved water quality, and greater periphyton production will increase invertebrate densities, improve B-IBI scores, and increase proportion of long-lived and sensitive taxa present.
Fish	Electrofishing surveys, mobile and fixed-array PIT-tag detection systems to track movement of tagged fish	Attenuated flow regime, improved habitat and water quality, and healthier populations of periphyton and benthic invertebrates will increase fish densities, growth and survival rates, species and size diversity, and diet composition.

Methodology

Study Design

Pipers Creek is the third largest stream in the City of Seattle and drains a total area of 6.5 km^2 in the far northwest corner of the city (City of Seattle 2007). Land use within the Pipers Creek watershed is 59% residential, and 31% combined transportation rights-of-way, commercial, and industrial. The remaining 10% of the basin is in open space and parks, primarily Carkeek Park, which contains the majority of the 3.2 km of mainstem and 4.8 km of tributary habitat that comprise Pipers Creek (City of Seattle 2007). While the condition of the riparian corridor in the park is good, over 20 outfall pipes deliver stormwater from developed uplands directly to the creek.

For this study, we selected the following five reaches within Carkeek Park: Venema Upper, Mohlendorph, Venema Lower, Pipers Lower, and Pipers Upper (Figure 1). Each study reach was ~50-m long (± 5 m so as not to truncate habitat units). The Venema Upper reach is the major receiving body for the planned NDS and is expected to benefit the most from this restoration action. The Mohlendorph reach contains no existing or planned NDS[1] and was selected as a reference for Venema Upper.

Two reaches downstream of Venema Upper were monitored to determine if potential project benefits persist beyond the immediate receiving body. These were Venema Lower (below the confluence of Venema Upper with Mohlendorph) and Pipers Lower (below the confluence of Venema Lower with Pipers Creek). The fifth study reach, Pipers Upper, was selected as an additional reference reach. The overall study design is a before-after, control-impact (BACI) approach with Venema Upper, Venema Lower, and Pipers Lower as potential impact reaches and Mohlendorph and Pipers Upper serving as controls. Data collection occurred over 2006-2009.

In addition to the five Pipers Creek study reaches, we began sampling similarly sized urban and forested streams in 2007. This sampling was conducted only for diatom taxonomic composition and metal soil and tissue concentrations, parameters for which we were not aware of any comparable regional datasets. Similar regional data for benthic invertebrates is already available through the Puget Sound Benthos online database.

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1 The Venema Natural Drainage System project has undergone a number of design revisions and may ultimately include a portion of the Mohlendorph subbasin.

Additional urban streams sampled were Thornton, Longfellow, Taylor, Fauntelroy, and Ravenna Creeks in Seattle. Forested study streams included Rock and Webster Creek in the Cedar River Basin; Struve Creek in the Bear Creek Basin; High Point, Holder, and East Fork Issaquah Creek in the Issaquah Creek Basin; Griffin Creek in the Snoqualmie River Basin; Deep Creek in southeast King County; and East Twin Creek on the Olympic Peninsula.

Sampling Parameters and Protocols

We collected data on three groups of stream organisms: fish, benthic invertebrates, and periphyton (the layer of biofilm covering the stream benthos). Benthic invertebrate and periphyton data were collected annually in early fall (September). Fish surveys were conducted in spring and fall 2006-2007 and thereafter in September only. Fish movement was monitored continuously using a combination of mobile and fixed-array detection systems for the passive integrated transponder (PIT) tag beginning in summer 2007.

Fish

Fish were sampled using a Smith Root backpack electrofisher. Within each reach, habitat units (pools, riffles, and glides) were classified using a modification of the methods described by Bisson et al. (1982). Block nets were placed at the lower and upper ends of each habitat unit to prevent movement of fish. Abundance estimates were obtained using the standard triple-pass depletion method (Carle and Strub 1978; Murphy and Willis 1996). All fish captured were identified to species, weighed, measured, tagged with PIT tags if > 60 mm in fork length (FL), and released back into the habitats from which they were removed.

Data from these collections were used to calculate taxonomic composition, total abundance, biomass, and density for each study reach. Because cutthroat *Oncorhynchus clarki* and rainbow trout *O. mykiss* are difficult to distinguish at smaller size classes, all trout less than 65 mm FL were initially classified simply as trout fry in the field. However, in a subsequent genetic analysis of fin clips from 96 fish sampled from Venema Upper and Lower in 2008 (50-162 mm FL), no evidence of *O. mykiss* was found (Dr. Gary Winans, NWFSC, pers. comm.). Therefore, we treat all fry as cutthroat for the purposes of density calculations.

In summer 2007, PIT-tag detection systems were installed at the confluence of Pipers and Venema Creek for remote monitoring of tagged juvenile salmonid and to estimate growth and survival—factors critical to determining the effectiveness of NDS projects. These systems are located in Pipers Creek immediately upstream from its confluence with Venema Creek and in Venema Creek 10 m upstream from its confluence with Pipers Creek (Figure 2). Data were downloaded remotely twice a week to monitor fish movement between study reaches. In addition, we conducted periodic surveys with a portable PIT tag antenna to examine fish movement throughout Venema Creek at a finer spatial (habitat unit) and temporal (biweekly) scales.

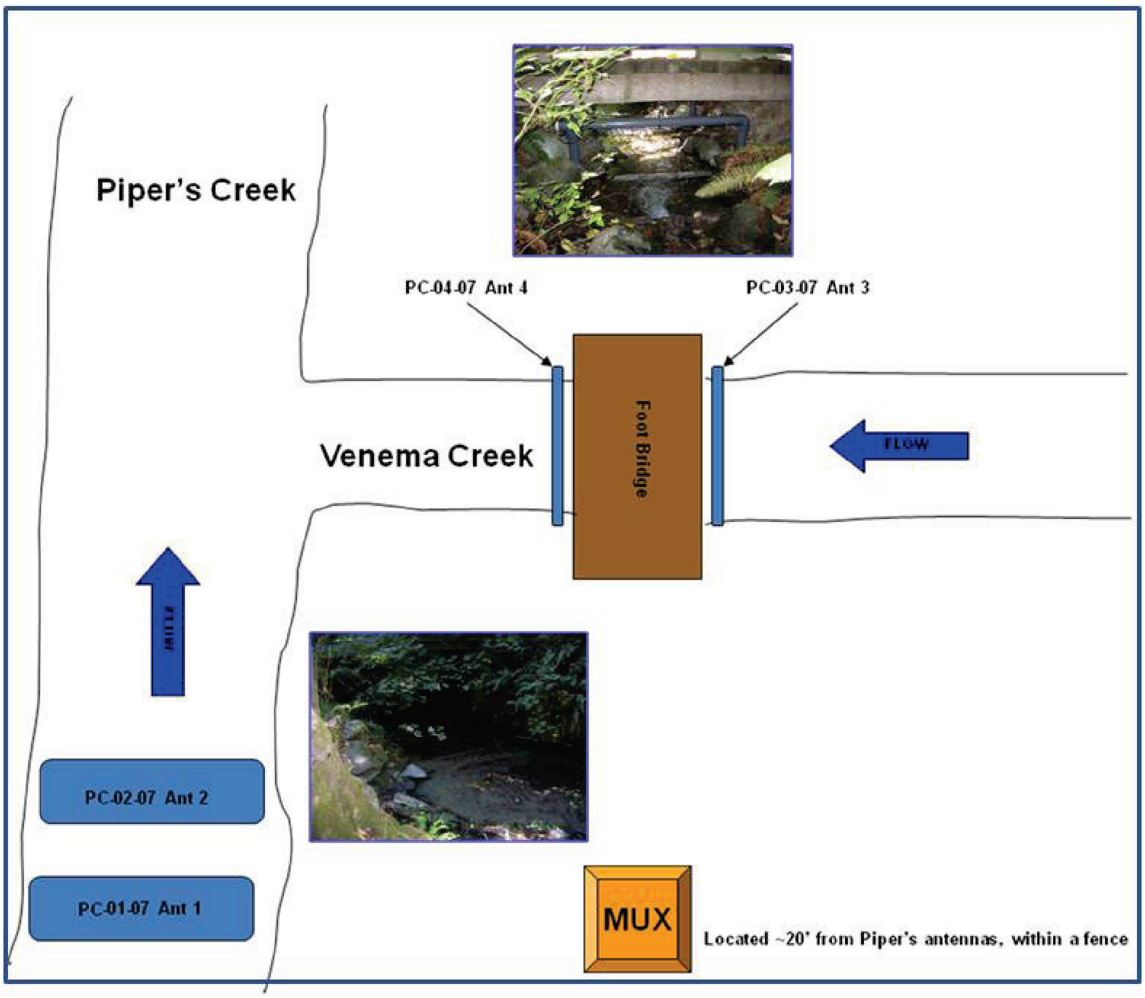

Figure 2. Location and photos of instream PIT-tag monitoring systems in Pipers and Venema Creeks. Each system consists of a power source, multiplex transceiver, and antenna array. Data are recorded and transmitted when fish come within range of the electromagnetic field transmitted by the antenna.

Benthic Invertebrates

Benthic invertebrates were sampled using a Slack sampler (500-µm mesh, 0.25-m^2 frame), a device developed for the National Water-Quality Assessment program (Moulton et al. 2002). One Slack sample was collected in each of five riffle habitat units within a given study reach. Given the historically low benthic invertebrate abundance observed at Pipers Creek (Laura Reed, SPU, pers. comm.), these five samples were then composited into one sample per reach. All samples were preserved in ethanol and sent to Aquatic Biology Associates Inc. for taxonomic analysis. Taxonomic data were then used to calculate total density, benthic index of biological integrity (B-IBI) scores, and associated metrics based on taxonomic and life history traits (Morley and Karr 2002; Merritt and Cummins 2008).

Periphyton

Periphyton was sampled from stream cobbles, with one cobble randomly selected from a streambed area adjacent to each of the five riffle habitats sampled for benthic invertebrates. Periphyton was removed from cobbles in the field and composited into one sample per reach. A portion of each sample was preserved in Lugol's solution and sent to Rhithron Associates Inc. for diatom taxonomic analysis. These data were used to calculate metrics based upon life history and disturbance tolerance (Van Dam et al. 1994; Teply and Bahls 2006). From the remaining periphyton sample a portion was reserved for contaminant analysis and the rest filtered onto two 47-mm glass-fiber filters for analysis of chlorophyll *a* concentration and ash-free dry mass (AFDM).

Chlorophyll *a* specifically measures the algal component of periphyton, whereas AFDM measures total periphyton biomass, including algae, fungi, bacteria, and microzoans (Steinman and Lamberti 1996). We extracted chlorophyll *a* from filters with acetone and measured the absorbance of the resulting supernatant using fluorometry (Marker et al. 1980). Ash-free dry mass was calculated following the gravimetric method (Steinman and Lamberti 1996). Chlorophyll *a* concentration and AFDM weights were converted to biomass per unit area (mg/cm^2 for AFDM, and µg/cm^2 for chlorophyll *a*) based on total rock surface area sampled at each site (Dall 1979).

Contaminants

An important goal of monitoring was to help determine whether bioswale filtration systems for the Venema NDS will effectively reduce contaminate delivery to the creek. To assess existing contaminant levels, we sampled metal concentration in fine sediments and periphyton, as well as in three benthic invertebrate genera: the filter-feeding blackfly *Simulium*, the collector-gathering mayfly *Baetis*, and the filter-feeding caddisfly *Hydropsyche*. We focused on metals because this class of compounds is often elevated in urban stream run-off, is frequently included in regional and national water quality monitoring programs, and can be measured relatively inexpensively. Our metal sampling efforts were inconsistent from year-to-year due to adjustments in sampling methodologies, changes in SPU data requests, and difficulty in collecting adequate tissue biomass for particular invertebrate taxa.

Zinc was analyzed in all years of the study, copper in all years except 2007, and lead in 2006 only. All metal sampling was conducted in September concurrent with biological sampling. Three surface soil samples were collected from depositional areas within each study reach using a plastic tablespoon to fill a 150-mL plastic sample jar. Soil samples were composited and sieved to select for fine particles using a U.S. Standard soil sieve (No. 200).

Periphyton was collected from rock cobbles as described above and freeze dried for 24-h until completely desiccated. Benthic invertebrate specimens were collected from throughout a study reach, pooled into individual samples, held in clean water for 24 h to clear gut contents, and freeze dried. All chemical analyses were conducted by Aquatic Research Inc. using acid digestion EPA method 3050B.

Stream Habitat

Along with biofiltration to reduce contaminants, a primary mechanism by which natural drainage systems are thought to help to restore urban creeks is through hydrologic modification via increased on-site retention. Hydrologic data is being collected by Seattle Public Utilities, and is not reported here. However, future changes in hydrology and associated sediment transport could change in-stream physical habitat. Although not a major focus of our study, we therefore included measures of physical habitat change in our monitoring efforts. Habitat-typing data was collected annually in conjunction with fish sampling, channel morphology measures were collected every spring, and sediment measures collected twice annually in spring and fall.

Channel Morphology

Channel morphology was measured for each study reach, with longitudinal profile and cross section surveys following methods outlined by Harrelson et al. (1994). Cross sections were marked with permanent rebar headpins placed outside the bankfull channel zone (area reasonably accessible to peak flow water levels). These headpins were surveyed relative to permanent benchmarks, which were established using existing cultural features. Beginning in 2007, three cross sections (rather than one) were surveyed within each study reach. Bedform was described by surveying points along each cross section at topographic break points or at 0.5-m intervals, whichever distance was smallest. Longitudinal profiles were measured along the entire 50-m length of each study reach by surveying points along the thalweg at slope breaks and dominant features. At a minimum, survey points were taken at the upstream and downstream end of each habitat unit (e.g., riffle, pool, etc.). These data will be needed for before/after comparisons once post-project monitoring data has been collected.

Particle Size Distribution

We characterized the stream bed using two methods: pebble counts (Wolman 1954) and volumetric sediment samples (Bunte and Abt 2001). To examine bed material size distribution, we conducted pebble counts in fall 2006-2009 and in spring 2007-2009 across the same five riffles sampled for benthic invertebrates in each study reach. From this data we calculated size distributions of bed material using the following three measures:

Fines (%):	Proportion of a 100-count sample with intermediate diameter ≤2 mm.
D_{50}:	Diameter of the median particle size
D_{84}:D_{50}:	Diameter at which 84% of pebbles are smaller divided by the diameter at which 50% of pebbles are smaller, a measure of hydraulic particle sorting

A volumetric sediment sample was collected annually from each study reach in 2007, 2008, and 2010 to characterize surface and subsurface particle sizes. The sample area (0.6 m^2) was excavated by hand in two layers: a surface layer, which extended from the surface to the average embedded depth of surface particles; and a subsurface layer, which extended from the average embedded depth of surface particles to a depth adequate for an equivalently sized sample. A three-sided plywood shield was used to isolate the sample area from moving water to avoid loss of fine material.

This material was dried, sieved, and weighed at U.S. Fish and Wildlife Service facilities in Lacey, WA to calculate percent fines, D_{50}, and D_{84}:D_{50} , as well as the ratio of surface-to-subsurface D_{50}—an indicator of sediment transport regime. Volumetric samples were processed and analyzed by U.S. Fish and Wildlife Hydrologist Paul Bakke.

Temperature

To evaluate temperature, Onset WaterTempPro™ continuously-recording temperature loggers were installed at each study reach in late September 2006. Loggers were suspended slightly above the channel bottom and set to record temperature at 1-h intervals. Data from temperature loggers were typically downloaded every 6 months and analyzed for daily and seasonal mean, minimum, and maximum temperatures. The Pipers Upper data logger was lost twice due to high flow events and temperature data from this reach is therefore missing from fall 2007 until spring 2009. Despite multiple attempts to re-locate the Mohlendorph logger to a more suitable location, this data recorder was often de-watered; thus temperature monitoring was discontinued at this reach.

Statistical Analyses

We examined patterns in our data at two scales: within-basin comparisons of data collected during 2006-2009 at the five Pipers study sites; and regional comparisons of similar data collected during 2007-2009 from other urban and forested streams. For within-basin comparisons, we used one-way ANOVA and tested for differences between means with Tukey's Honestly Significant Difference (HSD) test. For regional comparisons, we used a two-way ANOVA to examine differences among metrics by year and stream type (Pipers vs. urban vs. forested). Model residuals were examined for approximate normality, independence, and equality of variance and data were log or square-root transformed as appropriate. For ANOVA analyses, we used the statistical software packages R version 2.11.1.

In addition to testing for differences in individual metrics, we analyzed patterns of community structure in diatom taxa using a suite of complementary multivariate techniques available in the statistical software package PRIMER (version 6, Clarke and Gorley 2006). We square-root transformed these data to reduce the effects of right-skew, non-detections, and to down-weight the influence of common taxa with relatively high abundances (McCune andGrace 2002). We then created triangular resemblance matrices of pair-wise similarities between all sites based upon the transformed density of species using the Bray-Curtis distance (Clarke et al. 2006).

We used non-metric multidimensional scaling (nMDS) to graphically analyze patterns of diatom assemblage structure within Pipers and across basins. We tested for differences among groups using analysis of similarities (ANOSIM), a non-parametric analog to analysis of variance that tests for compositional differences among groups of sites based upon the ratio of rank similarities found in the resemblance matrix (Clarke and Warrick 1994).

We used a one-way ANOSIM to test for differences among Pipers study reaches across 2006-2009 and a two-way crossed ANOSIM with stream type and years as factors to test for differences among Pipers, urban, and forested sites from 2007 to 2009. We used a permutation test (999 iterations) to develop a null distribution that allowed calculation of exact *P* values. Among factors that were significantly different according to ANOSIM tests, we used the SIMPER procedure (Clarke and Warrick 2001) to determine which taxa contributed most to dissimilarities.

We conducted statistical power analysis to determine what level of change we can expect to detect over different frequencies of post-project monitoring. Based on our BACI experimental design, we applied two-sample *t*-tests to compare differences in treatment (Venema Upper, Venema Lower, and Pipers Lower) sample means relative to a reference reach (Pipers Upper). Due to dewatering, we concluded that Mohlendorph was not an appropriate reference reach.

We used a one-tailed hypothesis test to evaluate the hypothesis that differences between treatment and reference reaches would increase after NDS restoration. We calculated a pooled variance for each metric based on year-to-year variability of each treatment reach relative to Pipers Upper. We used a significance level (α) of 0.05 and power (β) of 0.80, and define effect size (δ) as the log ratio of treatment to reference sample means before and after NDS restoration.

In this approach, we assume that year-to-year variance after project completion will be similar to that observed before. To generate power curves, we varied δ to calculate the number of observations (in this exercise, years) needed to detect a particular level of change. We performed these calculations for biological response metrics, selecting one density metric and one rate or composition metric from each of three assemblages: fish, benthic invertebrates, and periphyton.

Results

Fish Composition and Abundance

Over the 4-year course of the study, five species of vertebrates were captured while electrofishing: cutthroat trout *Oncorhynchus clarki*, juvenile coho *O. kisutch*, chum salmon *O. keta*, Pacific giant salamanders *Dicamptodon tenebrosus*, and a single sculpin *Cottus* sp. (Appendix Table A). Chum salmon were detected only during spring in Venema Lower and Pipers Lower. Chum fry migrate to salt water shortly after emergence (Quinn 2005) and therefore were not present during our fall sampling (Quinn 2005). Because of their small size, juvenile chum were able to pass through our nets, and we likely sampled only a small portion of those present during spring 2006-2007. Juvenile coho salmon were captured only in spring and fall 2006 in Pipers Lower and Upper, and not thereafter. This finding may reflect the high rate of coho pre-spawn mortality observed in fall 2005 and 2006 (75 and 100% respectively of sampled fish; Thompson et al. 2007).

In all, 1,521 vertebrates were captured during six sampling events over 4 years (Appendix Table A). Total numbers of fish differed among reaches and were highest in the two Pipers Creek mainstem study reaches, followed by Venema Lower (one-way ANOVA, $P < 0.01$) (Table 2). Multiple comparisons indicted that numbers of vertebrates were significantly lower in Mohlendorph and Upper Venema than in all other reaches ($P < 0.05$). This was not surprising, given that only seven fish (cutthroat) have been captured from the Mohlendorph Creek study reach across all sampling periods to date (Appendix Table A).

Table 2. Mean values and standard deviations (small font) for fall vertebrate abundance and biomass (cutthroat only) collected at Pipers Creek 50-m long study reaches from 2006-2009.

	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
Cutthroat biomass (g)	102.0 (116.1)	20.3 (36.0)	363.0 (87.9)	1,221.1 (227.7)	1,069.9 (203.1)
Cutthroat (n)	9.3 (6.1)	1.5 (1.9)	46 (26.5)	156.0 (24.4)	98.0 (38.1)
Coho (n)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.3 (0.5)	0.8 (1.5)
Salamander (n)	0.0 (0.0)	0.0 (0.0)	0.8 (1.0)	0.8 (1.0)	0.3 (0.5)
Total all species (n)	9.3 (6.1)	1.5 (1.9)	46.5 (26.3)	157.0 (24.6)	99.0 (38.7)

Mohlendorph runs dry during low flows, which likely explains low fish use during most surveys. Both Mohlendorph and Pipers Upper differ in habitat conditions compared to the other three study reaches. The numbers of fish varied slightly from year-to-year, and was considerably lower in 2009 than previous years (Appendix Table A). Average cutthroat densities across all study reaches and years ranged 0-1.18 fish/m^2 and were significantly different among reaches (ANOVA, $P < 0.01$), similar to the differences among reaches found for total vertebrates (Figure 3).

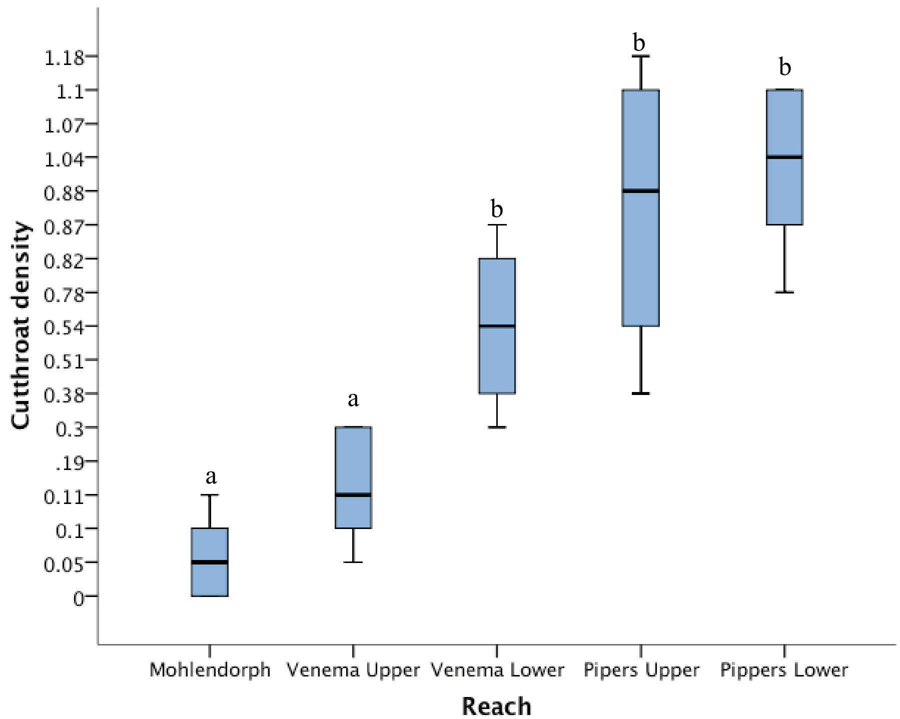

Figure 3. Box plots of cutthroat trout densities (fish/m^2) by study reach, 2006-2009. Dark bands indicate sample median, boxes represent interquartile range, and whiskers extend to sample minimum and maximum. Letters indicate that groups are significantly different (one-way ANOVA, $P < 0.05$, n = 4).

Fish Movement

A total of 679 cutthroat trout were PIT tagged during 2007-2009 sampling (no fish were tagged in 2006; Appendix Table A). The percent of tagged juvenile cutthroat detected migrating (passing the lowest antenna in Pipers Creek) from September to August varied from year-to-year (Figure 4). The majority of fish were detected within 9 months after tagging. For example, of fish tagged in 2007, 88% were detected during the fall, winter, and spring following tagging, while for those tagged in 2008 and 2009, only

20 and 18%, respectively, were detected during the same period. For fish tagged in Venema, the proportion detected passing the lowest downstream antenna later in the same year was 53, 31 and 46% for fish tagged in 2007, 2008, and 2009 respectively (Figure 4). These data suggest that about half of the tagged fish either moved into Pipers Creek or migrated to Puget Sound during this period.

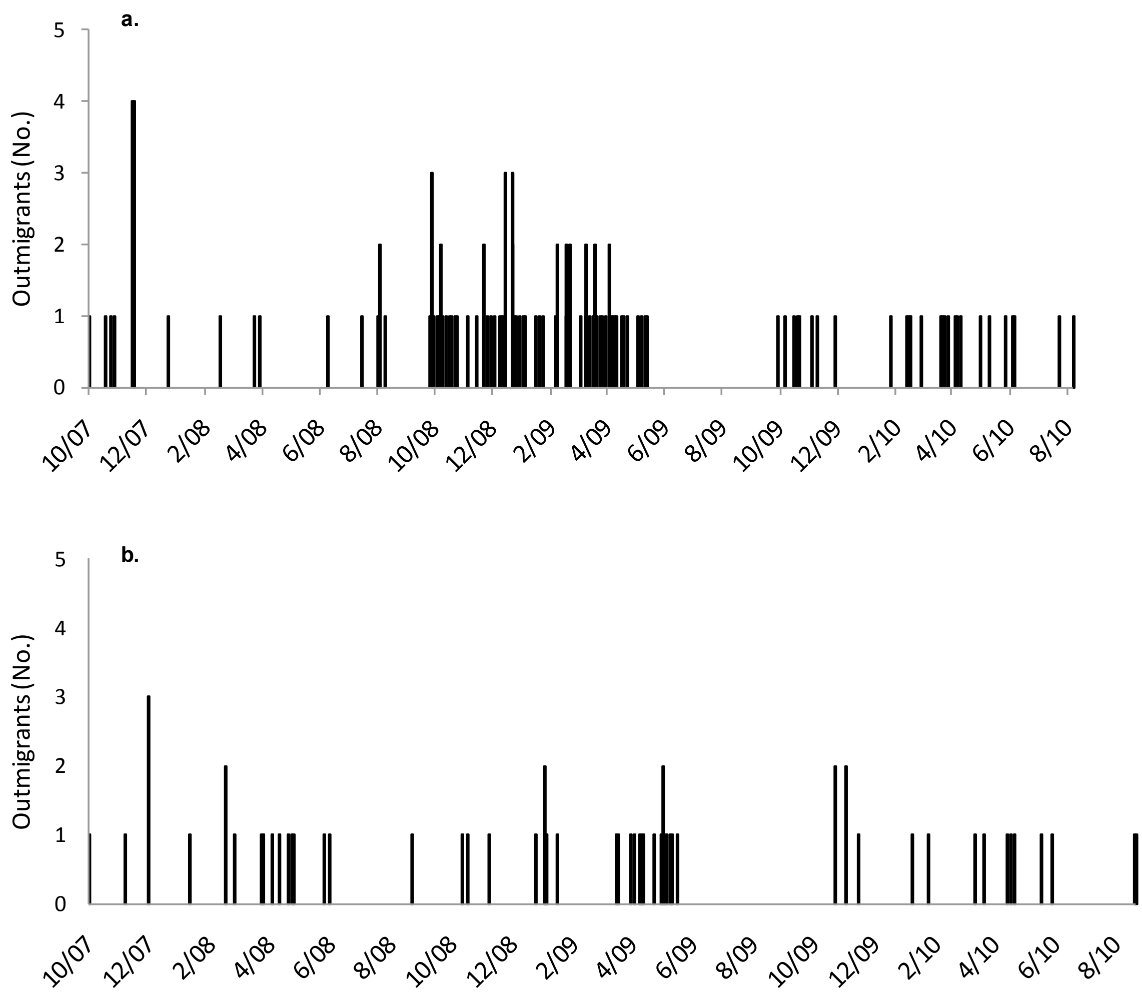

Figure 4. Total number of PIT-tagged juvenile cutthroat trout detected migrating each day from a) Venema Creek b) Pipers Creek. If a fish was detected on multiple days, the last day of detection was used as its migration day.

To examine fine-scale movement of tagged fish and overall survival, we also conducted periodic surveys (approximately every 2 weeks) of Venema and Mohlendorph creeks using a hand-held portable PIT tag antenna. A total of 28 manual scans were conducted between October 2007 and September 2009. During these surveys, 164 fish were detected within Venema Creek. Most fish had moved less than 100 m, though distance moved ranged 0-302 m. In fact, 50% of the fish were not detected outside of the habitat unit in which they were tagged.

This was consistent with findings from other studies on juvenile trout and salmon, which show that the non-migratory portion of the population moves relatively short distances (Roni and Fayram 2000; Kahler et al. 2001). The maximum number of biweekly encounters of a given tagged fish was 10, although most fish were detected only once or twice after tagging (68%). The longest period of time between tagging and manual detection was from a cutthroat tagged in September 2007 and detected in the same reach in July of 2009. Approximately 20% of the fish tagged in Venema were not detected after tagging, either by periodic surveys or by stationary PIT tag detection systems; these fish were assumed to have died during the study period (20% mortality).

Growth

A total of 50 cutthroat trout tagged in 2007 or 2008 were recaptured during electrofishing in 2008 and 2009. All but one of these fish were recaptured in Pipers Upper (29 fish) or Pipers Lower (20 fish). Only 2 fish were recaptured from a different reach than where they were initially tagged, and only 4 fish tagged in 2007 were recaptured in both 2008 and 2009. Because the period between tagging and recapture ranged 362-730 d, we standardized growth rates for weight (g/d) or length (mm/d). Average daily growth in mm/d was 0.11 (SD 0.03) and 0.15 (SD 0.03) in Upper and Lower Pipers, respectively, and these growth rates were significantly different (t = -4.37, $P < 0.01$). Growth rates ranged 0.05-0.24 mm/d in length and 0.02-0.13 g/d in weight.

Benthic Invertebrates

A total of 50 different benthic invertebrate taxa were observed across the five Pipers Creek study reaches during 2006-2009[2] (Appendix Table B). Mean taxa richness at study reaches ranged from 19 to 27 (Table 3). In contrast, over 40 taxa are commonly found in forested streams of the Puget Sound lowlands (Morley and Karr 2002). Across the Pipers study reaches, the three most numerically abundant taxa—the black fly genus *Simulium* spp., the disturbance-tolerant mayfly nymph *Baetis tricaudatus*, and the midge family Chironomidae—typically accounted for 50-80% of the total benthic invertebrates at a site. Pipers study reaches were characterized by low taxa richness for EPT (Ephemeroptera, Plecoptera, Trichoptera) taxa richness. (Appendix Table C).

Table 3. Mean values and standard deviations (in parentheses) for benthic invertebrate metrics collected at Pipers Creek study reaches from 2006-2009. Benthic Index of Biological Integrity (B-IBI) calculations are based on the "Species-Family" level of taxonomic resolution applied in the Puget Sound Stream Benthos database: Chironomids identified to family, other insects specified to species or the lowest rank practical.

	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
B-IBI metrics	614 (540)	227 (57)	680 (471)	598 (255)	1,643 (1,263)
Total taxa (n)	27 (3.8)	19 (2.2)	27 (8.2)	24 (3.0)	23 (1.0)
Mayfly (Ephemeroptera) taxa (n)	3 (0.6)	2 (0.8)	3 (0.6)	2 (0.5)	3 (0.6)
Stonefly (Plecoptera) taxa (n)	4 (1.0)	2 (0.8)	3 (1.3)	4 (0.5)	3 (0.6)
Caddisfly (Trichoptera) taxa (n)	4 (1.3)	3 (0.5)	3 (0.8)	4 (1.3)	3 (0.8)
Long lived taxa (n)	2 (0.8)	1 (0.5)	2 (0.5)	2 (1.0)	2 (0.8)
Intolerant taxa (n)	1 (0.8)	1 (0.6)	1 (0.5)	1 (0.5)	1 (0.6)
Clingers taxa (n)	9 (2.5)	5 (2.4)	8 (1.3)	9 (3.5)	8 (2.0)
Dominance (% top 3 taxa)	69 (5.9)	62 (7.5)	67 (8.3)	72 (7.4)	75 (5.1)
Predator individuals (%)	6 (1.5)	12 (8.9)	7 (1.5)	8 (2.6)	5 (0.5)
Tolerant individuals (%)	14 (6.3)	24 (5.8)	24 (6.8)	46 (10.8)	44 (19.7)
Final B-IBI Score	21 (2.0)	19 (5.3)	17 (1.2)	18 (3.7)	16 (2.8)

2 Calculation based on the "Species-Family" level of taxonomic resolution applied in the Puget Sound Stream Benthos database: Chironomids identified to family, other insects specified to species or the lowest rank practical.

Taxa tolerant to high levels of disturbance typically comprised one-quarter to over one-half of individuals present in a sample, and very few long-lived or intolerant taxa were found in any study reach (Table 3). Within the Pipers watershed, Venema Upper had a slightly higher number of EPT taxa and lower percentage of tolerant individuals compared to other reaches (Table 3). Across our five Pipers study reaches, invertebrate density was significantly lower at Mohlendorph than at Pipers Upper (one-way ANOVA, $P < 0.05$, n = 4).

Relative to both forested and urban streams, invertebrate density was significantly lower for reaches within Pipers Creek (two-way ANOVA, basin effect $P < 0.05$, no year effect detected, n = 5). We did not detect any statistically significant difference in B-IBI scores among the five Pipers reaches. While Venema Upper typically scored highest within the Pipers Creek watershed, the overall range in B-IBI across reaches and years was small (14-26).

All study reaches fell within the "very poor" to "poor" categories (B-IBI of 0-26, Figure 5a). Overall, these results were very similar to those reported by Seattle Public Utilities for other urban creeks in Seattle (Figure 5b). Compared to forested streams in the region, wherein B-IBI scores range 42-50, Seattle urban creeks are in poor biological health. B-IBI scores at forested sites were significantly higher than those at Pipers and at other urban creeks (two-way ANOVA, basin effect $P < 0.05$, no year effect detected, n = 5).

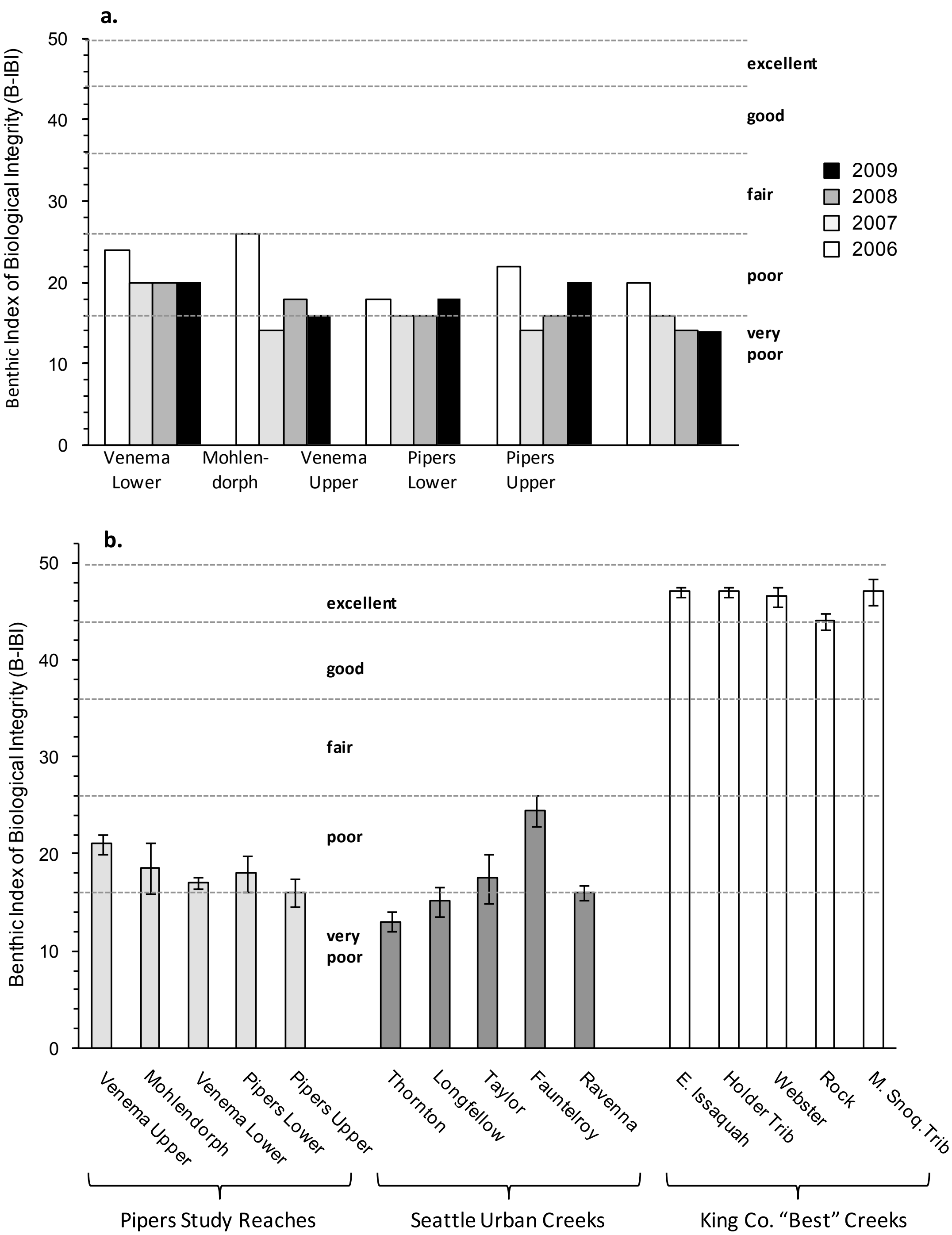

Figure 5. Benthic index of biological integrity scores (B-IBI) at Pipers Creek study reaches (a) from 2006-2009 and (b) relative to five other urban streams in Seattle and five forested streams in King County. Data are plotted as mean values over the most recent 4 years of data collection with error bars showing ±1 SE. Reference stream data from Puget Sound Stream Benthos website.

Periphyton

Diatom Composition

Taxonomic analysis of the diatomaceous portion of periphyton samples identified a total of 135 unique species across the 5 Pipers Creek study reaches over all 4 study years. Overall, Pipers reaches were characterized by a high proportion of species classified as eutraphentic (tolerant of inorganic nutrient enrichment) and a relatively small proportion of taxa tolerant to low dissolved oxygen conditions (Table 4). Among individual study reaches, species richness ranged 14-42, relative abundance of metal-tolerant taxa 4-45%, siltation taxa 5-40%, polysaprobous taxa (tolerant of organic nutrient enrichment) from 6-75%, and N-autotrophic taxa from 62-97% (Appendix Table D).

Table 4. Mean values for diatom metrics collected at Pipers Creek study reaches from 2006-2009. Metrics are based on diatom taxonomic, functional, and disturbance life history attributes. Note that eutraphentic taxa are those tolerant of nutrient enrichment, polysaprobous taxa are tolerant of organic enrichment, and N-autotrophic taxa are those requiring dissolved inorganic nitrogen. Standard deviations in parenthesis.

		Diatom community attributes, 2006-2009 (SD)				
	Predicted urbanization response	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
Community structure						
Species richness	↓	25.0 (7.1)	23.0 (7.9)	27.0 (10.1)	31.8 (7.4)	27.8 (8.7)
Diversity (Shannon H')	↓	2.7 (0.5)	2.7 (0.6)	2.9 (0.7)	3.0 (0.3)	2.2 (0.6)
Dominant taxon (%)	↑	43.3 (12.1)	37.3 (23.4)	37.7 (15.2)	36.4 (14.1)	64.1 (6.9)
Metal impacts (%)						
Metals tolerant taxa	↑	28.6 (13.1)	23.8 (9.0)	13.3 (4.7)	13.7 (3.2)	6.0 (2.8)
Disturbance taxa	↑	3.7 (2.8)	19.8 (35.0)	17.7 (21.9)	10.1 (14.8)	17.7 (31.0)
Sediment impact (%)s						
Siltation taxa	↑	9.9 (7.0)	27.8 (14.8)	11.4 (8.6)	14.3 (7.1)	7.4 (2.9)
Motile taxa	↑	29.5 (9.6)	34.4 (16.9)	24.5 (14.0)	28.0 (15.2)	14.0 (6.4)
Nutrient enrichment (%)						
Low DO taxa	↑	5.0 (5.0)	3.9 (2.7)	2.0 (1.2)	2.1 (2.4)	1.7 (0.9)
Eutraphentic taxa	↑	85.7 (4.0)	59.9 (29.9)	70.2 (24.1)	77.5 (16.1)	74.2 (30.5)
Polysaprobous taxa	↑	35.4 (12.5)	56.0 (28.4)	24.0 (14.1)	25.4 (10.5)	10.6 (6.0)
N-autotrophic taxa	↑	87.5 (6.7)	71.7 (15.2)	87.4 (9.6)	87.1 (7.4)	94.7 (2.0)

Metal-tolerant taxa were present in lower proportions at Upper Pipers relative to both Mohlendorph and Upper Venema, and polysaprobous taxa were present in lower proportions at Upper Pipers relative to Upper Venema (one-way ANOVA, $P < 0.05$, n = 4). We did not detect any differences among sites in species richness or in the proportion of taxa tolerant to siltation or to inorganic nutrient enrichment (eutraphentic taxa).

Based on multivariate analysis of raw data, diatom assemblage differed significantly at Mohlendorph relative to all sites except Lower Venema (one-way ANOSIM, $P < 0.05$). For all other diatom assemblage data, Pipers sites overlapped with one another (Figure 6a). Of the four species identified as contributing most to the dissimilarities between Mohlendorph and other reaches, the two more prevalent in Mohlendorph are regularly found in wet or moist places: *Nitzschia inconspicua* and *Planothidium frequentissimum*. In contrast, the taxa more common at other Piper sites, *Cocconeis placentula* and *Rhoicosphenia abbreviata*, are mainly found in water.

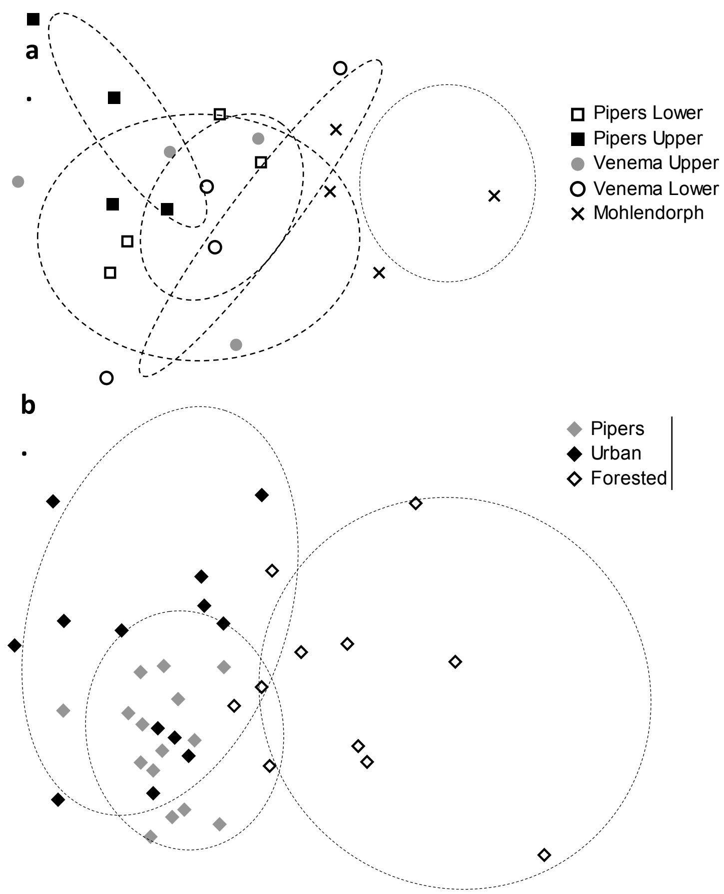

Figure 6. Non-metric multidimensional (nMDS) plots of diatom assemblage data (square-root transformed) for (a) Pipers Creek study reaches, 2006-2009 and for (b) Pipers Creek reaches relative to other urban and forested streams, 2007-2009.

Although taxa richness was similar among diatom assemblages in Pipers Creek reaches, other urban creeks, and forested streams, diatom community composition differed among these groups in several ways (Figure 7). Pipers Creek reaches contained significantly higher proportions of diatom species classified as tolerant of sedimentation and of both organic (polysaprobous), and inorganic (eutraphentic) enrichment (Figure 7; two-way ANOVA, $P < 0.05$, no year effect detected).

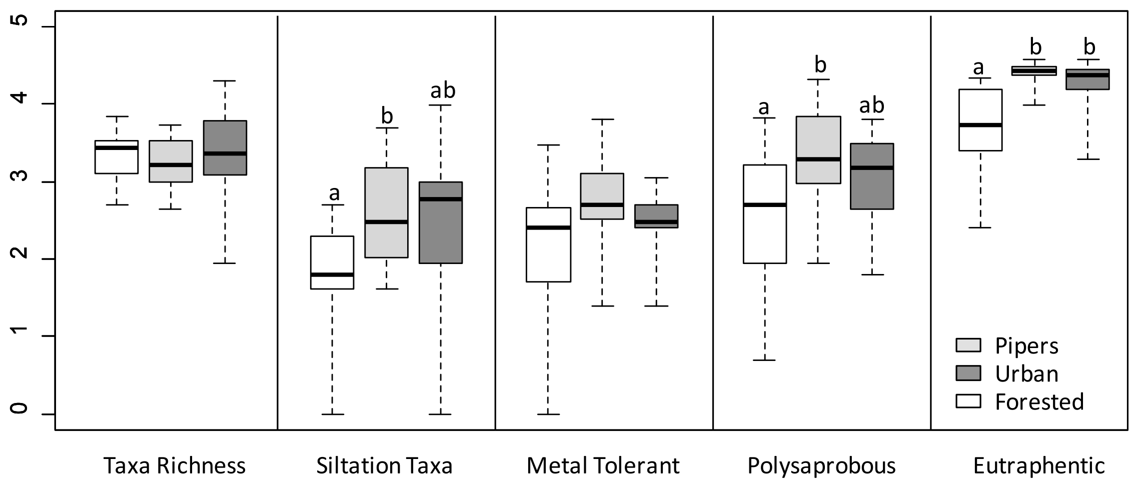

Figure 7. Boxplots for five diatom metrics from Pipers Creek study reaches relative to other regional urban and forested streams. Dark bands indicate sample median, boxes represent interquartile range, and whiskers extend to sample minimum and maximum. Letters indicate that groups are significantly different (two-way ANOVA, $P < 0.05$, n = 5). Units on the X-axis differ by metric, with taxa richness representing the number of unique species present within a sample and siltation, metal, polysaprobous, and eutraphentic taxa representing the respective percentage of individuals tolerant of siltation, heavy metals, organic enrichment, and inorganic enrichment. Data are log transformed.

Eutraphentic taxa were also more abundant in other urban streams than in forested streams, but abundance in Pipers Creek reaches did not differ from that in other urban streams for any of the five metrics tested. Multivariate analysis of underlying diatom taxonomic structure displayed similar results. Pipers and other urban streams overlapped significantly, while forested sites were taxonomically distinct (Figure 6b; two-way ANOSIM, $P < 0.05$, year effect detected between 2008 and 2009).

Based on SIMPER analysis, 72% of the dissimilarity between Pipers Creek reaches and forested streams was attributed to differences in relative abundance of six families. Of these six, Catenulaceae, Achnanthaceae, Bacillariaceae, Rhoicospheniaceae were more prevalent in Pipers Creek reaches and other urban streams, while Achnanthidiaceae and Gomphonemataceae were more abundant in forested streams.

In general, species from the four families abundant in Pipers Creek reaches are tolerant of high levels of organic and inorganic enrichment and low-to-moderate levels of oxygen saturation, and they prefer alkaline waters (pH > 7). In contrast, species from the families abundant in forested sites are generally less tolerant of organic enrichment and prefer high levels of oxygen saturation and neutral-to-alkaline water.

Biomass

Total periphyton biomass was relatively low at all Pipers Creek reaches, with ash-free dry mass (AFDM) ranging 0.06-0.11 mg/cm^2 (Table 5). Densities for both AFDM and chlorophyll *a* were typically higher in the upper and lower Pipers Creek reaches relative to Venema and Mohlendorph (Appendix Table E). These patterns in periphyton biomass data were likely due to a combination of natural and anthropogenic factors. A less confined channel, more open canopy, and warmer summer water temperatures likely contribute to greater algal production in Pipers Creek than in Venema and Mohlendorph Creeks.

Table 5. Mean values for periphyton metrics collected at Pipers Creek reaches, 2006-2009. Total periphyton density is expressed as mg ash-free dry mass (AFDM) per cm^2 rock surface and algal density as µg Chlorophyll *a* per cm^2 rock surface. Autotrophic index is the proportion of total periphyton biomass composed of algae; it is calculated as the ratio of AFDM to Chlorophyll *a*. Standard deviations in parentheses.

	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
AFDM (mg/cm^2)	0.06 (0.04)	0.08 (0.04)	0.07 (0.05)	0.10 (0.07)	0.11 (0.07)
Chlorophyll *a* (µg/cm^2)	0.23 (0.26)	0.22 (0.08)	0.18 (0.05)	0.37 (0.24)	0.61 (0.56)
Autotrophic index	732.9 (719.7)	378.0 (169.9)	350.5 (176.7)	277.0 (91.7)	208.5 (70.3)

Differences in the frequency of scour events, sedimentation rates, and water chemistry may also have contributed to the differences in periphyton biomass between study reaches. In 2009 and 2006, autotrophic index values were very high in Upper Venema, indicating that algae comprised a smaller proportion of total periphyton biomass than in other study reaches. However, this pattern was not consistent across all sample years.

Contaminants

Over the course of the study, metal concentrations per dry gram of fine sediment ranged 73-517 µg for zinc and 28-68 µg for copper. For periphyton, zinc ranged 31-3,549 µg/g and copper 3-369 µg/g, and for benthic invertebrates, zinc was found at levels of 24-1,697 µg/g and copper at 2-369 µg/g (Appendix Table F). We found no significant differences in zinc concentration among the five study reaches for any of the five sample groups tested (Table 6).

Table 6. Mean values and standard deviations (small font) for copper and zinc concentrations in fine sediment, periphyton, and benthic invertebrates collected at Pipers Creek study reaches from 2006-2009. All values are units of µg/g dry weight.

	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
Zinc (µg/g)					
Fine sediment	101 (24.6)	135 (29.8)	109 (43.0)	207 (113.8)	300 (190.1)
Periphyton	78 (36.2)	193 (176.2)	212 (217.1)	141 (79.3)	1,025 (1684.0)
Invertebrates					
Black Fly	182 (33.1)	285 (183.0)	195 (46.0)	203 (36.8)	369 (208.3)
Caddisfly	198 (34.6)	192 (7.1)	231 NA	143 (120.2)	164 (198.0)
Mayfly	790 (159.4)	1,697 NA	819 (282.9)	1,284 (307.9)	1,001 NA
Copper (µg/g)					
Fine sediment	30 (0.0)	33 (1.4)	30 (1.9)	33 (0.4)	61 (9.7)
Periphyton	21 (12.7)	90 (110.3)	59 (8.0)	56 (33.1)	153 (189.5)
Invertebrates					
Black Fly	47 (14.7)	42 NA	71 (43.0)	53 (27.2)	58 (20.8)
Caddisfly	27 (0.7)	31 (7.1)	40 NA	22 (19.1)	17 (20.5)
Mayfly	190 (208.9)	76 NA	215 (218.6)	114 (90.3)	47 NA

We were unable to test for differences in mayfly taxa due to low sample size. Copper concentrations were significantly higher in fine sediments from Upper Pipers relative to the other four reaches (one-way ANOVA; $P < 0.01$), but did not differ for periphyton or invertebrate taxa. The highest concentrations of both copper and zinc at a given site were typically observed in mayfly taxa or in periphyton (Table 6).

Metal concentrations were elevated in the five Pipers Creek study reaches relative to forested streams for zinc, but not copper (Figure 8). There were no significant differences in metal concentrations between Pipers and other urban streams, nor a year effect detected over 2007-2009. For fine sediment, black fly, and mayfly samples, zinc concentrations were significantly higher at both Pipers reaches and other urban streams relative to forested streams (Figure 8a; two-way ANOVA, $P < 0.05$ for stream type). In periphyton samples, zinc concentrations were significantly higher in urban streams relative to forested, but Pipers periphyton concentrations were intermediate. We did not detect any difference in caddis fly metal concentrations by stream type. Nor did we observe any differences in copper concentrations by stream type for any of the five groups sampled (Figure 8b).

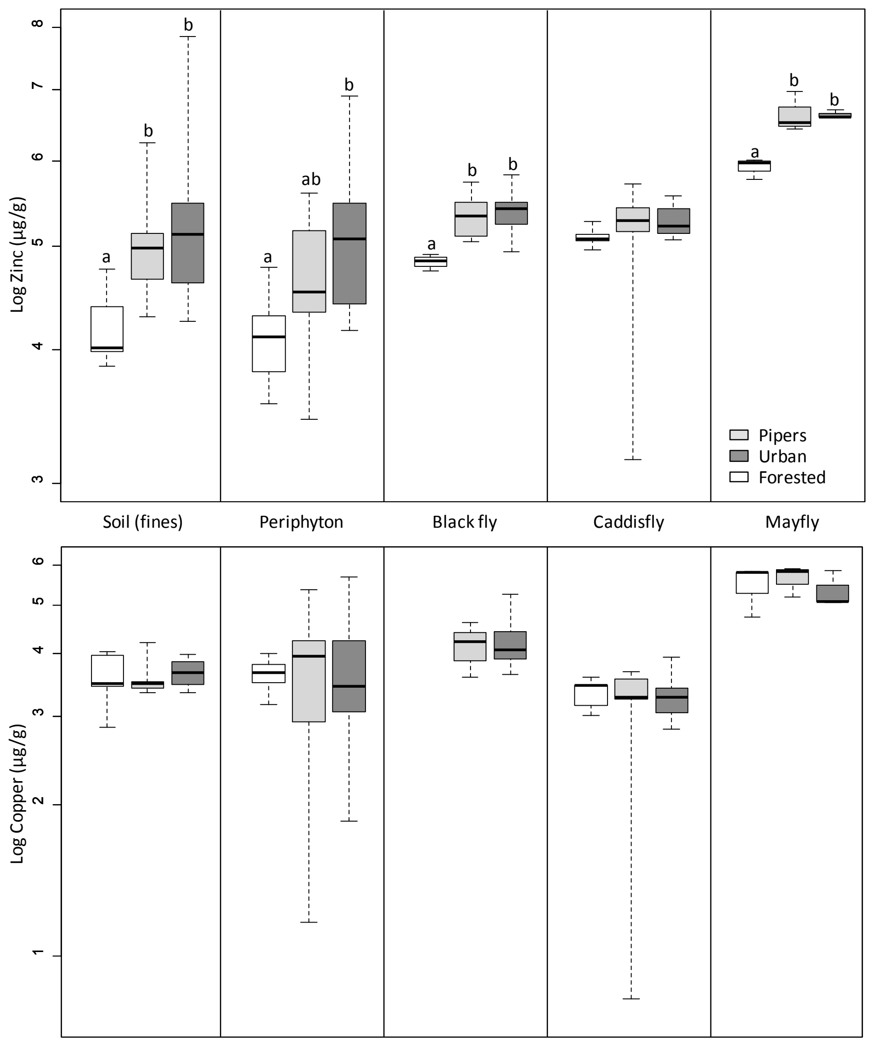

Figure 8. Boxplots showing relative concentrations of zinc (upper panel) and copper (lower panel) in five Pipers Creek study reaches, 2007-2009. Values are µg/g dry weight and are log transformed. Dark bands indicate median, boxes represent interquartile range, and whiskers indicate minimum and maximum. Letters indicate significant differences between groups (two-way ANOVA, $P < 0.05$, n = 5 except where sample biomass inadequate).

Stream Habitat

Habitat surveys were conducted in conjunction with fish surveys to help explain changes in biota due to the NDS project (Appendix Table G). Surveys in 2006, 2007 and 2008 show that the number of habitat units was fairly stable between years within reaches, with the highest number of habitat units present in Venema Lower (Table 7). The largest decrease in habitat units was in Mohlendorph, where unit number decreased from 13 to 6 units between summer of 2007 and summer of 2008.

Table 7. Mean values and standard deviations (parenthesis) for stream survey metrics collected at Pipers Creek study reaches, 2006-2009. Study reaches were approximately 50 m in length: area measurements are m^2.

	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
Wetted area (m^2)	57.3 (1.0)	33.0 (9.5)	57.3 (11.8)	163.0 (10.6)	115.8 (16.7)
Pool area (m^2)	4.3 (1.0)	11.5 (11.9)	30.8 (13.3)	71.0 (38.3)	46.3 (7.7)
Pool volume (m^2)	6.3 (1.0)	0.9 (0.6)	9.6 (5.0)	28.2 (13.0)	21.1 (17.0)
Units (n)	6.3 (1.0)	9.0 (4.1)	12.5 (1.7)	8.0 (1.2)	9.3 (2.5)
Pools (n)	1.8 (1.0)	4.3 (2.1)	6.0 (0.8)	4.0 (0.8)	4.0 (1.4)

Pool Area

Both study reaches on Pipers mainstem have several well-constructed log weirs that should inhibit changes in the number of pools and limit reduction in pool area. Percent pool area differed among study reaches (ANOVA; $P < 0.01$), with mutiple comparisons indicating that Upper Venema and Molendorph were different from most other reaches (Tukey; $P < 0.05$). The observed reduction in percent pool area from 2006 to 2008 suggests filling of some pools with fine or coarse sediment. The proportion of pool area was relatively small in study reaches other than Pipers—particularly in both Venema Upper and Mohlendorph (< 25% in all years and seasons). Small low-gradient streams typically have pool areas of nearly 50%, while a pool area of 25% suggests high sediment load or low levels of instream woody debris or other structure (Beechie and Sibley 1997).

The higher proportion of pool area and greater flow in both reaches of Pipers likely explains why fish numbers are much greater in these reaches. Only Venema Lower showed a substantial increase in percent pool area in 2009. Residual pool depth, which is a good measure of changes in pool quality and sediment supply over time, was fairly consistent among seasons in Pipers and Venema Lower, but dropped dramatically from spring 2006 to spring 2007 in Venema Upper. This was likely due to a landslide above this reach, which transported large amounts of fine and course sediment into the study reach and filled many pools. In summer 2008, measurements in Venema Upper showed that residual pool depth increased from the lower level in spring 2007.

Channel Morphology

Based on longitudinal profile surveys, Venema Upper was the steepest study reach with a 5-6.5% gradient. The two mainstem Pipers reaches had the lowest gradientat 2-3%, with Venema Lower and Mohlendorph reaches at 3-4%. Although for the most part, cross section data indicated that channel morphology has not changed greatly at most study reaches over the last year, high flows in December 2007 did contribute to bank erosion in some reaches (e.g., Pipers Upper #2 and Venema Upper #3; Figure 9).

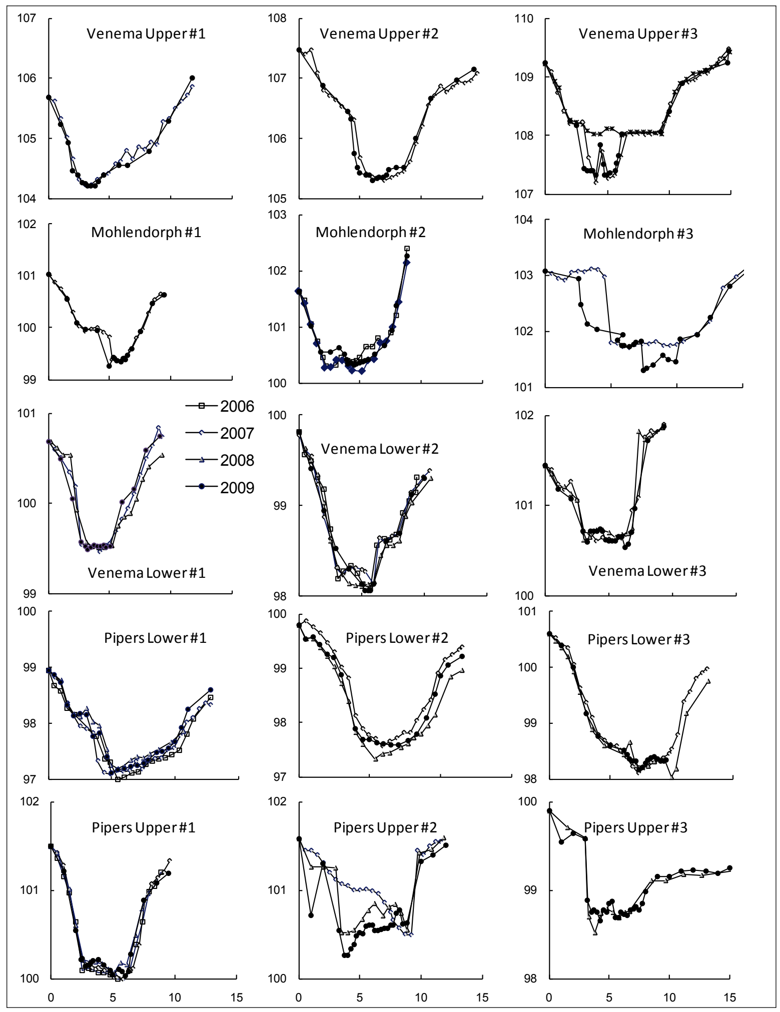

Figure 9. Relative elevations at Pipers Creek cross sections. Note that only one cross-section per reach was collected in 2006. Other missing years are due to field error. All units are in meters.

These measurements provide baseline data, and as we collect additional pre- and post-NDS data we expect to see changes in pool area, number of habitat units, and pool quality (residual depth). These factors are known to change in response to changes in fine and coarse sediment as well as runoff; thus we expect improvements in residual depth and pool number and area after construction of NDS projects.

Sediment and Particle Size

Pebble count data collected over 2006 to 2009 indicated that median particle size (D_{50}) is smallest in Venema Upper (7-27 mm) and largest in Mohlendorph and Pipers Upper (19-39 mm; Appendix Table H). The Venema Upper study reach consistently contained the highest proportion of fine particles (10-37%), and Mohlendorph and Pipers Upper the smallest (≤ 10%; Figure 10).

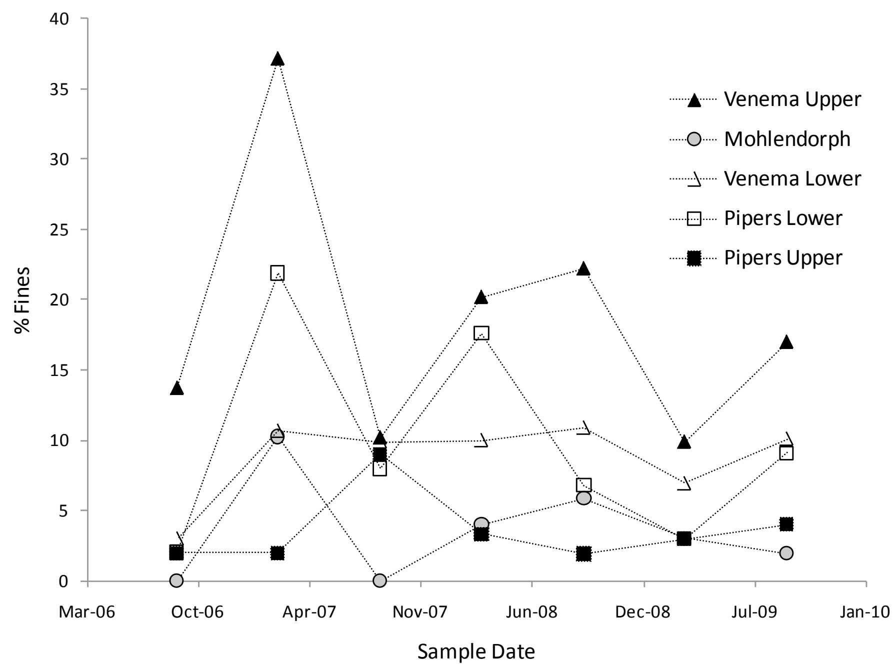

Figure 10. Proportion of fine sediments (intermediate diameter ≤ 2mm) present in the stream bed surface, based on Wolman pebble counts collected at Pipers study reaches from 2006-2009.

Similar trends were observed from volumetric sampling of the surface and sub-surface layers (Table 8). Based on statistical analysis of pebble count data, D_{50} was significantly higher at Mohlendorph and Pipers Upper relative to Venema Upper, and percent fines was significantly higher at Venema Upper relative to all other sites except Pipers Lower (one-way ANOVA, $P < 0.05$, n = 7). We did not detect any differences among sites in $D_{84:50}$. Due to low sample size (n = 3), we did not conduct statistical testing on volumetric data.

Table 8. Mean values and standard deviations (parentheses) for streambed particle size metrics collected at Pipers Creek study reaches from 2006-2010.

	Venema Upper	Mohlendorph	Venema Lower	Pipers Lower	Pipers Upper
Wolman Pebble					
Fines (%)	19 (9.4)	4 (3.6)	9 (2.9)	10 (7.4)	4 (2.6)
D50 (mm)	18 (6.3)	28 (5.6)	25 (8.1)	19 (6.2)	28 (5.6)
D84:50	3.1 (1.2)	2.3 (0.6)	2.5 (0.4)	2.4 (0.5)	2.1 (0.3)
Volumetric Surface					
Fines (%)	15 (11.6)	4 (4.6)	11 (6.93)	11 (9.5)	7 (6.8)
D50 (mm)	24 (13.5)	44 (20.0)	29 (21.43)	21 (7.9)	22 (5.1)
D84:50	2.1 (0.7)	1.7 (0.3)	3.0 (2.2)	2.1 (0.4)	1.9 (0.3)
Volumetric Sub-Surface					
Fines (%)	22 (2.5)	16 (4.0)	20 (3.0)	21 (3.0)	16 (4.4)
D50 (mm)	16 (8.0)	16 (3.6)	12 (3.9)	13 (0.8)	15 (4.0)
D84:50	3.0 (0.5)	2.3 (0.2)	2.8 (0.3)	2.9 (0.4)	2.3 (0.4)
D50 (S:SS*)	1.6 (1.0)	2.7 (0.7)	2.2 (1.0)	1.6 (0.5)	1.5 (0.1)

* Surface to sub-surface

Temperature

Differences in mean daily temperature among Pipers reaches were greatest in summer and winter (Figure 11). During July and August, average maximum daily temperature ranged 13.1-16.1°C (Appendix Table I). Summer temperatures were highest in mainstem Pipers reaches and lowest in Venema Upper, followed by Venema Lower. Winter minimum temperatures varied slightly less from reach to reach, typically ranging over 2°C (Table 9). During December and January, temperatures were lowest in Venema Lower and Pipers Lower, and warmer in Venema Upper and Pipers Upper.

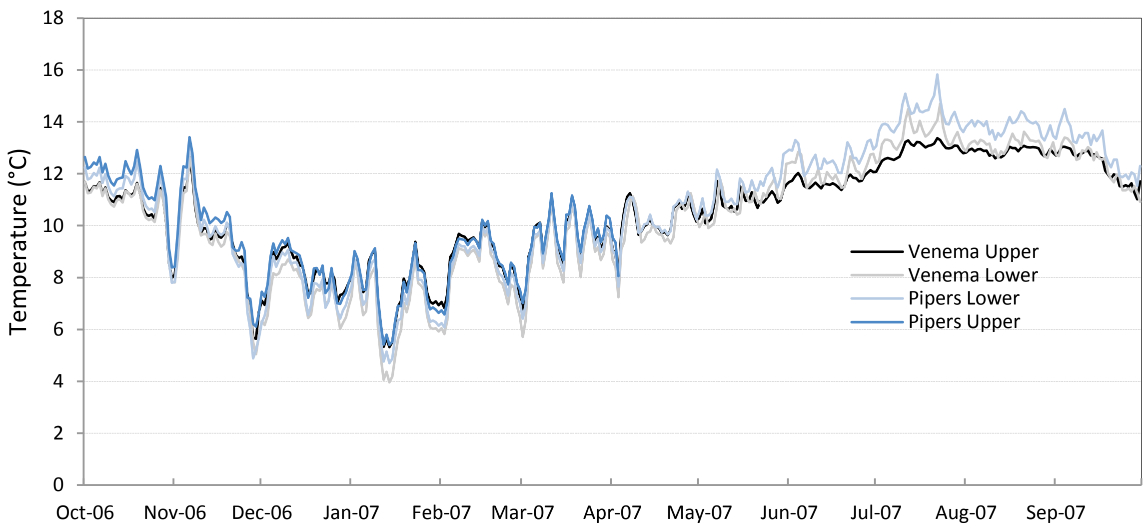

Figure 11. Mean daily temperature at Pipers Creek study reaches, plotted from 1 October 2006 to 30 September 2007. Data from Mohlendorph is excluded due to logger dewatering. Data from subsequent illustrate similar trends.

Table 9. Mean temperature metrics collected at Pipers Creek study reaches from 2006-2009. Temperature records at Piper Upper are based on only 1 year for most months due to logger loss and dewatering. The temperature logger at Mohlendorph was discontinued due to intermittent flow. Standard deviations shown in parentheses.

	Mean temperature (°C)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Venema Upper												
Min	6.8 (1.3)	6.9 (1.0)	6.9 (1.2)	7.9 (1.1)	9.9 (0.8)	11.2 (0.5)	12.1 (0.4)	12.4 (0.0)	10.8 (0.7)	9.3 (1.0)	7.6 (2.2)	5.2 (1.8)
Mean	8.0 (0.9)	8.5 (0.6)	8.8 (0.6)	9.7 (0.3)	10.9 (0.2)	11.8 (0.4)	12.6 (0.3)	12.8 (0.0)	12.2 (0.2)	10.9 (0.1)	9.8 (0.5)	7.7 (0.2)
Max	9.1 (0.8)	9.9 (1.1)	10.3 (1.1)	12.0 (0.9)	11.9 (0.2)	12.5 (0.3)	13.3 (0.2)	13.5 (0.1)	13.6 (0.3)	12.4 (1.1)	11.1 (0.3)	9.5 (1.4)
Venema Lower												
Min	5.6 (1.4)	5.9 (0.8)	6.1 (0.6)	7.0 (1.2)	9.6 (1.1)	11.2 (0.6)	12.3 (0.4)	12.6 (0.0)	10.6 (0.9)	9.0 (1.0)	7.3 (2.0)	4.2 (1.7)
Mean	7.2 (1.1)	7.9 (0.7)	8.2 (0.8)	9.4 (0.5)	10.9 (0.2)	12.0 (0.5)	13.0 (0.4)	13.2 (0.0)	12.3 (0.2)	10.8 (0.1)	9.5 (0.6)	6.8 (0.3)
Max	8.6 (1.1)	9.8 (1.4)	10.3 (1.5)	12.4 (1.0)	12.5 (0.7)	13.4 (1.0)	13.9 (0.6)	14.1 (0.0)	14.4 (0.7)	12.7 (1.5)	11.0 (0.4)	9.2 (1.8)
Pipers Lower												
Min	6.8 (2.6)	7.1 (2.4)	7.3 (1.8)	8.5 (2.2)	11.1 (1.2)	11.9 (0.6)	12.8 (0.5)	13.2 (0.0)	11.4 (0.7)	10.1 (2.0)	8.7 (2.5)	5.8 (2.1)
Mean	7.8 (1.4)	8.1 (0.8)	8.2 (0.3)	9.7 (0.4)	11.5 (0.2)	12.3 (0.7)	13.6 (0.5)	13.9 (0.0)	12.2 (1.4)	11.2 (0.2)	9.9 (0.7)	7.3 (0.3)
Max	8.9 (1.1)	9.8 (1.3)	10.1 (1.0)	12.3 (0.9)	12.9 (0.6)	13.5 (0.7)	14.7 (0.6)	14.8 (0.1)	14.2 (2.6)	12.4 (0.6)	10.9 (0.3)	8.9 (1.7)
Pipers Upper												
Min	3.1 NA	1.2 NA	1.2 NA	5.9 (4.8)	5.0 (5.3)	10.4 (1.6)	13.0 NA	13.0 NA	11.5 (0.8)	5.4 NA	5.0 NA	NA
Mean	7.5 NA	7.1 NA	8.4 NA	9.5 (0.7)	9.7 (1.9)	13.0 (0.6)	14.5 NA	14.3 NA	13.1 (0.6)	11.1 NA	9.2 NA	NA
Max	9.9 NA	10.4 NA	12.1 NA	13.9 (3.3)	12.6 (0.7)	15.9 (0.9)	16.1 NA	15.8 NA	14.9 (0.9)	15.2 NA	12.1 NA	NA

Power Analyses

Power curves describing the relationship between sample and effect size illustrate that metrics describing taxonomic composition have greater power to detect change than do simple density measurements (Figure 12). This is particularly true for algal and invertebrate density, which due to their high year-to-year variability will likely require far more than four years of pre and post-project data to detect even a 100% change (i.e., doubling). In contrast, the low variability of B-IBI and diatom similarity coefficients indicate that it will be possible to detect smaller changes (20-40%) between treatment and reference reaches over a shorter timeframe. Variability in instantaneous trout growth rates between treatment and references reaches was also very low and shows promise as a response metric. However, these data should be interpreted with caution as they are based on relatively few individuals.

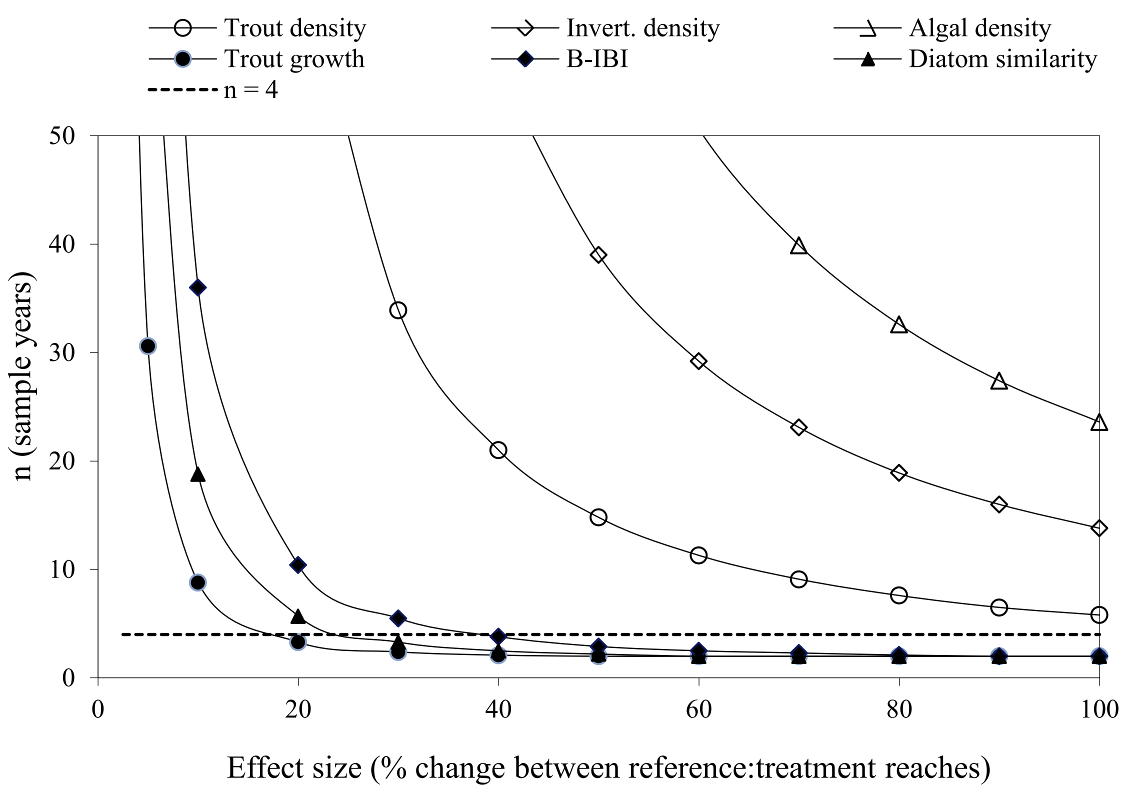

Figure 12. Power curves describing the relationship between effect size and sample size necessary to achieve 80% power at the 0.05 significance level for biological response metrics. Trout growth is instantaneous growth determined as the difference in fork length divided by total number of days since recapture (typically a year), and diatom similarity refers to the Bray-Curtis similarity index as calculated in the statistical software package PRIMER.

Discussion

Similar to many heavily urbanized streams in the Puget Sound area, the fish fauna in Pipers Creek is dominated by cutthroat trout (Matzen et al. 2008). Densities of cutthroat trout in both Pipers Creek study reaches and in lower Venema Creek were similar to those reported for Thorton Creek by Lanz et al. (2009): higher than other urban streams in the Seattle area, but within the range for small relatively undisturbed forested streams (Rosenfeld et al. 2000). Higher cutthroat trout densities in these reaches was surprising given the poor water quality and biotic conditions.

However, the location of our study reaches in Carkeek Park, their proximity to Puget Sound, and the sizeable chum salmon run in Pipers Creek may provide additional food resources. There is also considerable spawning of sea-run cutthroat trout in Pipers Creek (Thompson et al. 2008), and the lack of other vertebrate species suggests little competition for food, space, and reproduction. In contrast, fish densities in Upper Venema and Mohlendorph were similar to those in heavy urbanized streams, but lower than those found in most natural streams.

The fact that more than half of tagged fish were detected at our PIT tag antennas suggests that a sizeable portion of the population migrates into the lower part of Pipers Creek, and most likely onto Puget Sound. Few juvenile trout appeared to migrate during summer low flow periods, but migration peaked in fall, with a fairly constant number of fish moving during winter and spring. This was consistent with movement patterns observed for juvenile salmon and trout in other streams (Kahler et al 2001; Roni and Quinn 2001; Roni et al. 2009; Pess 2009). These movement patterns also explain in part why densities were highest in fall compared to spring sampling as many fish may immigrate to sea during this period.

The small numbers of fish moving past our antennas each day made it hard to relate fish movement to flow events, but data on more extensive tagging studies in natural streams suggests that flow is only one movement trigger (P. Roni unpublished data). That we were able to account for the majority of the fish tagged in Venema Creek over the course of our study suggests that most overwinter mortality occurs when fish leave our study area. While estimates of survival for coastal cutthroat trout are rare, this estimate is higher than other ongoing PIT tag studies on steelhead and cutthroat trout (Roni et al. 2009). However, our study is unique in that we were not only able to detect all out-migrating fish, but also scan the entire stream to determine the fate of tagged fish that did not migrate.

Fish are typically apex predators in stream ecosystems, but they rely upon the larger stream foodweb, of which benthic invertebrates and periphyton are major components. Surveys of both benthic invertebrates and periphyton have long been used in stream assessments nationally and internationally (Barbour et al. 1999; Moulton et al. 2002; Hering et al. 2006). Different organisms may also be more or less sensitive to different stressors, of which there is typically no shortage in urban environments. In the Pacific Northwest there is a particularly rich history of benthic invertebrate monitoring with the development of the regional Benthic Index of Biological Integrity (B-IBI; Karr et al) and the online publication of the Puget Sound Stream Benthos database.

Primary production by periphyton is a major food source for higher trophic levels (Thorp and Delong 2002), and these organisms are often sensitive to changes in water chemistry and fine sediments (Stevenson et al. 2008; Walker and Pan 2006). From a biological assessment perspective, we may learn more by focusing on assemblages of periphyton, which have more taxa present in our study systems than other study organisms. We observed only 4 fish species in our study reaches, but identified 50 different benthic invertebrate taxa and 135 diatom species.

Across all study reaches, B-IBI scores were consistent from year to year, providing a good response metric with which to detect relatively small changes in post-restoration biological health (Figure 12). The availability of reference datasets across the region is also a valuable monitoring resource. We do not expect to see post-restoration B-IBI scores in Pipers Creek reach levels observed in undeveloped forested streams. However, an improvement from poor (scores of 16-26) to fair (26-36) is a reasonable restoration goal.

Although variability in benthic invertebrate density is typically high both spatially and temporally, we found that invertebrate densities at Pipers were significantly lower than for other regional forested and urban streams. This may be due to the heavy shading typical of forested ravines like that of Carkeek Park, or may reflect some aspect of anthropogenic disturbance particularly deleterious in this basin. Low benthic invertebrate densities could have implications for fish health in terms of available prey resources. This is an area we are currently investigating further.

Results of the diatom PRIMER analysis clearly discriminated between taxonomic composition at Pipers reaches relative to forested streams (Figure 7b). We hypothesize that following NDS completion, this pattern will shift towards less overlap between Pipers and urban streams, and greater overlap between Pipers and forested streams. Low year-to-year variability in taxa composition and abundance (measured using Bray-Curtis similarity coefficients) indicated that diatom taxonomic structure will also be a useful response metric (Figure 12). Evaluations of diatom community structure have been used widely in bioassessment protocols in other parts of the world, but in the Pacific Northwest, less work has been done on the development of appropriate diatom metrics (but see Walker and Pan 2006; Stevenson et al. 2008). Because metrics developed in one region may not always be appropriate for another, the applicability of species disturbance classifications and response metrics used in this study may be limited (Potopova and Charles 2007). However, our observations of relatively high proportions of diatoms tolerant of sedimentation and nutrient enrichment at Pipers reaches were consistent with fine sediment data and reports that nutrient concentrations and fecal coliform bacteria frequently exceed state water quality criteria in Pipers Creek (City of Seattle 2007).

The purpose of contaminant sampling was not to determine if Pipers Creek exceeded particular water quality criteria, but to establish baseline data for evaluating NDS stormwater filtration. Both copper and zinc are naturally present in aquatic and terrestrial environments via geologic weathering. In trace amounts, these elements are essential for plants and animals, but at higher concentrations they become toxic. Along with a host of other contaminants, zinc and copper are often found in elevated levels in urban stormwater runoff (Davis et al. 2001).

Anthropogenic sources of zinc include building siding, galvanized metal rooftops and gutters, automobile tire wear, and moss-killers. Sources of copper include vehicle brake wear, atmospheric deposition, and plumbing, electrical, and roofing materials. We observed significantly elevated levels of zinc at Pipers reaches relative to forested streams, but no differences in copper concentrations. Although copper has received much scrutiny recently due to its sub-lethal effects upon juvenile salmonids (Hecht et al. 2007), zinc is typically present in higher concentrations than copper in urban stormwater runoff (Davis et al. 2001).

Our ability to draw inferences from contaminant data was confounded in part by difficulties in collecting adequate biomass of invertebrate taxa common to both urban and forested streams. Previous studies have reported that mayflies may be particularly sensitive to metals (Maret et al. 2003). While we observed the highest metal concentrations in mayfly taxa, our statistical power was limited due to small sample size.

Patterns observed in substrate metrics were likely due to differences in geology and in the extent of in-stream structure between the study reaches. Glacial till in upper Mohlendorph Creek is more erosion-resistant, and numerous in-stream grade-control structures are present in mainstem Pipers Creek; nevertheless, the erosion of outwash deposits in the steep upper Venema Creek ravine is a major source of sediment in the watershed (City of Seattle 2007). This was reflected in the smaller-diameter (D_{50}) and higher proportion of fines observed in Venema Upper and downstream study reaches. In the subsurface layer, Mohlendorph and Pipers Upper had relatively low sand content compared to Venema reaches and Pipers Lower. This would be consistent with ongoing active sand transport from Venema Creek, while other branches have depleted their sand supply.

Observed ratios of D_{84} to D_{50} were low for a typical gravel bed stream with moderate sediment load, and could indicate low sediment sorting—due to close proximity to a source, or lack of diverse source areas. Subsurface $D_{84:50}$ values were more typical of a gravel bed stream in equilibrium with its sediment load (Parker and Toro-Escobar 2002). A possible interpretation of these sediment data is that all of these stream reaches are currently close to equilibrium with their sediment load, but that prior to 2008, these reaches experienced an input of fine sediment, which has been diminishing in the surface layers of the streambed since that time.

Recommendations

- **Conduct post-project monitoring over multiple years:** Given natural year-to-year variability, a minimum of 3 years of post-project monitoring should be conducted following NDS construction to detect potential changes.

- **Focus on composition and not only on density:** taxonomic structure and rate metrics (such as growth and movement for fish) have lower year-to-year variability and better reflect biological stream health.

- **Invest greater time in invertebrate contaminant sampling:** We recommend investing greater field time in the future to ensure adequate sample biomass for chemical analyses, and sampling across multiple feeding guilds (Goodyear and McNeill 1999; Richardson and Kiffney 2000).

- **Increase number of study reaches:** Based on intermittent flow conditions, we conclude that Mohlendorph is not an appropriate reference reach for many response metrics. We recommend including both more upstream reference reaches and downstream treatment reaches in future sampling.

- **Expand study beyond Pipers Creek:** This monitoring effort was an important component of project evaluation, but ultimately should be expanded beyond one basin in order to more adequately assess NDS effectiveness.

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Appendix

Appendix Table A. Annual fish numbers and biomass (cutthroat only) found in Pipers Creek Watershed study reaches from 2006-2009. Values in parentheses indicate number of individuals PIT tagged of total captured. Spring sampling was discontinued after 2007.

		Biomass (g)	Total number captured (n)				
Year	Season	Cutthroat	Cutthroat	Coho	Chum	Salamanders	All species
Pipers Upper							
2006	Spring	969	38	15	0	1	54
2006	Fall	1,286	115	3	0	0	118
2007	Spring	468	29	0	0	0	29
2007	Fall	1,146	116 (100)	0	0	0	116
2008	Fall	1,044	120 (97)	0	0	1	121
2009	Fall	804	41 (21)	0	0	0	41
Pipers Lower							
2006	Spring	1,186	65	14	1	1	81
2006	Fall	1,071	155	1	0	1	157
2007	Spring	1,194	47	0	6	3	56
2007	Fall	1,511	162 (139)	0	0	2	164
2008	Fall	1,291	183 (102)	0	0	0	183
2009	Fall	1,011	124 (86)	0	0	0	124
Venema Upper							
2006	Spring	237	5	0	0	0	5
2006	Fall	38	6	0	0	0	6
2007	Spring	45	2	0	0	0	2
2007	Fall	272	17 (17)	0	0	0	17
2008	Fall	79	11 (11)	0	0	0	11
2009	Fall	19	3 (3)	0	0	0	3
Venema Lower							
2006	Spring	280	10	0	5	1	16
2006	Fall	487	43	0	0	0	43
2007	Spring	362	14	0	9	1	24
2007	Fall	364	36 (34)	0	0	0	36
2008	Fall	299	83 (42)	0	0	1	84
2009	Fall	302	21 (21)	0	0	2	23
Mohlendorph							
2006	Spring	0	0	0	0	0	0
2006	Fall	0	0	0	0	0	0
2007	Spring	16	1	0	0	0	1
2007	Fall	74	4 (4)	0	0	0	4
2008	Fall	7	2 (2)	0	0	0	2
2009	Fall	0	0	0	0	0	0

Appendix Table B. Relative abundance of benthic invertebrate taxa collected across all Pipers Creek study reaches from 2006-2009. Insects were typically identified to the genus or species level, except Diptera, which were often left at family. Non-insects range in resolution from class to species.

				Relative abundance (%)			
Class	Order	Family	*Genus spp.*	2006	2007	2008	2009
Insecta	Coleoptera	Dytiscidae	---------------				< 1
		Elmidae	*Lara avara*	1	< 1	< 1	< 1
		Elmidae	*Zaitzevia spp.*		< 1		
Insecta	Diptera	Ceratopogoninae	---------------	< 1	< 1	< 1	
		Chironomidae	---------------	11	18	17	5
		Dixidae	*Dixa spp.*	< 1	< 1	1	< 1
		Dolichopodidae	---------------		< 1		
		Empididae	*Chelifera/Metachela*	< 1	< 1	< 1	< 1
		Forcipomyiinae	---------------	< 1	< 1		< 1
		Limoniidae	*Austrolimnophila spp*			< 1	
		Limoniidae	*Molophilus spp*			< 1	
		Muscidae	---------------	< 1			
		Mycetophilidae	---------------			< 1	< 1
		Pedicciidae	*Dicranota spp*	< 1	< 1	< 1	< 1
		Psychodidae	*Pericoma spp*	< 1	< 1		< 1
		Simuliidae	*Simulium spp*	20	32	19	36
		Stratiomyidae	*Caloparyphus spp*				< 1
		Thaumaleidae	---------------		< 1		
		Tipulidae	*Tipula spp*	< 1	< 1	< 1	< 1
Insecta	Ephemeroptera	Baetidae	*Baetis tricaudatus*	26	17	29	26
		Heptageniidae	*Cinygma spp*	1	1	1	1
		Heptageniidae	*Cinygmula spp*		1		
		Heptageniidae	*Epeorus spp*		< 1		
		Leptophlebiidae	*Paraleptophlebia spp*	< 1	< 1		< 1
Insecta	Plecoptera	Chloroperlidae	*Sweltsa spp*	< 1	< 1	1	< 1
		Nemouridae	*Malenka spp*	< 1	< 1	< 1	1
		Nemouridae	*Soyedina spp*	< 1	< 1	< 1	< 1
		Nemouridae	*Zapada cinctipes*	13	13	13	13
		Nemouridae	*Zapada Oregonensis*	3	1	3	1
Insecta	Trichoptera	Glossosomatidae	*Glossosoma spp*	< 1	< 1	< 1	< 1
		Hydropsychidae	*Hydropsyche spp*		1	< 1	1
		Hydropsychidae	*Parapsyche almota*	4	4	7	5
		Lepidostomatidae	*Lepidostoma spp*				< 1
		Limnephilidae	*Dicosmoecus gilvipes*	< 1			
		Limnephilidae	*Psychoglypha spp*	< 1			< 1
		Philopotamidae	*Wormaldia spp*	< 1			
		Rhyacophilidae	*Rhyacophila Betteni*			< 1	

Appendix Table B. Continued.

Class	Order	Family	*Genus spp*	Relative abundance (%) 2006	2007	2008	2009
Insecta	Trichoptera	Rhyacophilidae	*Rhyacophila Brunnea*	< 1	< 1	< 1	< 1
		Rhyacophilidae	*Rhyacophila Hyalinata*		< 1		
Arachnida	Acari	---------------	---------------	1	< 1	1	1
Bivalvia	Veneroida	Sphaeriidae	*Pisidium spp*	1	< 1	< 1	< 1
Crustacea	Amphipoda	Crangonyctidae	*Crangonyx spp*	7	5	5	2
Crustacea	Ostracoda	---------------	---------------	< 1	< 1		< 1
Gastropoda	Basommatophora	Physidae	*Physa spp*	< 1			
	Basommatophora	Planorbidae	*Menetus spp*				< 1
	Neotaenioglassa	Hydrobiidae	*Pristinicola hemphilli*				< 1
Hirudinea	---------------	---------------	---------------	< 1			
Nematoda	---------------	---------------	---------------	< 1	< 1	< 1	< 1
Oligochaeta	---------------	---------------	---------------	10	2	2	3
Turbellaria	---------------	---------------	---------------	2	2		2

Appendix Table C. Annual benthic invertebrate data from Pipers Creek reaches collected over 2006-2009.

	Venema Upper				Mohlendorph				Venema Lower				Pipers Lower				Pipers Upper			
	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006
Density (n/ m^2)	324	311	1422	398	224	252	281	149	586	322	1368	445	345	434	710	901	1892	362	3,288	1030
B-IBI metrics (raw data)																				
Total taxa (n)	32	24	27	24	19	22	18	17	39	25	25	20	28	25	21	23	22	24	22	23
Mayfly taxa (n)	2	2	3	3	2	2	3	1	2	2	3	3	2	2	3	2	2	2	3	3
Stonefly taxa (n)	5	4	5	3	2	1	2	3	5	3	3	2	4	4	3	4	3	2	3	2
Caddisfly taxa (n)	5	2	3	4	2	3	3	3	4	2	3	3	5	2	3	4	4	3	3	2
Long lived taxa (n)	1	2	2	3	1	1	1	2	2	2	3	2	1	1	2	3	1	2	2	3
Intolerant taxa (n)	1	1	2	0	0	1	1	0	1	1	1	0	1	1	1	0	1	1	0	0
Clingers taxa (n)	8	6	8	12	2	5	5	8	8	7	8	10	8	6	8	14	7	7	7	11
Dominance (% top 3 taxa)	60	71	73	71	70	52	64	63	66	58	78	65	74	71	80	62	82	74	74	70
Predator individuals (%)	6	8	5	5	12	12	2	24	5	8	6	8	10	9	4	8	5	6	5	5
Tolerant individuals (%)	20	8	18	8	22	24	32	18	34	21	19	22	43	61	46	35	29	71	30	48
Final B-IBI	20	20	20	24	16	18	14	26	18	16	16	18	20	16	14	22	14	14	16	20

Appendix Table D. Annual diatom assemblage data from Pipers Creek reaches collected over 2006-2009.

	Predicted urban response	Venema Upper 2009	Venema Upper 2008	Venema Upper 2007	Venema Upper 2006	Mohlendorph 2009	Mohlendorph 2008	Mohlendorph 2007	Mohlendorph 2006	Venema Lower 2009	Venema Lower 2008	Venema Lower 2007	Venema Lower 2006	Pipers Lower 2009	Pipers Lower 2008	Pipers Lower 2007	Pipers Lower 2006	Pipers Upper 2009	Pipers Upper 2008	Pipers Upper 2007	Pipers Upper 2006
Community Structure																					
Species Richness	↓	20	35	20	25	14	33	21	24	20	42	24	22	25	26	36	40	26	39	18	28
Diversity (H')	↓	2.49	3.40	2.10	2.73	2.80	3.21	2.92	1.88	3.08	3.75	2.38	2.26	2.58	3.27	3.24	3.08	1.99	2.92	1.61	2.1
Dominant taxon (%)	↑	43	35	60	34	22	29	26	72	25	24	54	47	51	19	44	32	71	55	66	64
Metal impacts (%)																					
Metal tolerant taxa	↑	45	21	15	33	24	32	27	11	19	14	12	8	13	17	15	10	6	10	4	4
Disturbance taxa)	↑	1	3	3	8	1	4	1	72	1	22	1	47	1	3	4	32	3	3	1	64
Sediment impacts (%)																					
Siltation taxa	↑	6	20	6	8	28	40	37	7	24	9	8	5	12	24	14	7	7	12	5	6
Motile taxa	↑	40	34	18	25	38	49	41	10	45	22	17	14	28	49	20	15	17	21	6	12
Nutrient enrichment (%)																					
Low DO taxa	↑	2	12	0	6	2	6	6	1	3	2	3	0	1	1	6	1	1	3	1	2
Eutraphentic taxa[a]	↑	87	80	90	86	69	78	78	15	86	54	95	45	90	82	84	54	88	82	97	29
Polysaprobous taxa[b]	↑	51	36	20	34	65	75	70	14	43	25	18	10	25	38	27	12	10	19	7	6
N-autotrophic taxa[c]	↑	87	78	94	90	68	62	63	94	74	87	93	95	88	77	89	94	94	92	97	96

[a] Eutraphentic taxa are those tolerant of nutrient enrichment
[b] Polysaprobous taxa are tolerant of organic enrichment
[c] Nitrogen autotrophic taxa require dissolved inorganic nitrogen

Appendix Table E. Annual periphyton density data from Pipers Creek reaches collected over 2006-2009.

	Venema Upper				Mohlendorph				Venema Lower				Pipers Lower				Pipers Upper			
	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006
Ash-free dry mass (mg/cm^2)	0.02	0.05	0.08	0.11	0.04	0.06	0.08	0.13	0.03	0.03	0.08	0.14	0.03	0.06	0.12	0.19	0.04	0.08	0.19	0.15
Chlorophyll *a* ($\mu g/cm^2$)	0.01	0.16	0.60	0.14	0.24	0.10	0.27	0.28	0.14	0.13	0.18	0.25	0.15	0.34	0.29	0.72	0.23	0.21	1.40	0.59
Autotrophic index	1,732	286	139	775	183	578	310	441	178	236	423	564	210	228	411	260	164	283	135	252

Appendix Table F. Annual zinc and copper concentrations for soil, periphyton, and benthic invertebrates samples collected from Pipers Creek reaches over 2006-2009. In 2006 we measured copper, lead, and zinc in surface waters and all categories shown (Morley et al. 2007). In 2007 we sampled for zinc only, discontinued sampling of surface water, collected black fly larvae only, and sieved soil samples to analyze only smaller size fractions (< 0.074 mm) (Morley et al. 2008). In 2008, we resumed copper analysis, and sampled black fly, mayfly, and caddisfly (Morley et al. 2009). In 2009 sampling remained the same as in 2008 except that mayflies were not collected. Water sample collection and lead analysis was not resumed after 2006 but see Morley et al. (2007).

	Venema Upper				Mohlendorph				Venema Lower				Pipers Lower				Pipers Upper			
	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006
Zinc (µg/g)																				
Soil	73	113	117	--	101	145	158	--	81	158	87	--	110	333	180	--	160	517	225	--
Periphyton	61	77	129	46	31	91	223	429	162	76	77	532	255	103	75	132	92	189	270	3,549
Black fly	166	232	166	164	--	--	156	415	--	246	155	184	--	206	165	239	309	251	238	678
Mayfly	--	678	--	903	--	--	--	1,697	--	619	--	1020	--	1,066	--	1,501	--	--	--	1,001
Caddisfly	222	173	--	--	187	197	--	--	231	--	--	--	58	228	--	--	24	304	--	--
Copper (µg/g)																				
Soil	30	30	--	--	34	32	--	--	31	28	--	--	33	34	--		68	54	--	--
Periphyton	18	35	--	10	3	214	--	53	52	58	--	68	53	91	--	25	19	70	--	369
Black fly	36	64	--	42	--	--	--	42	--	102	--	41	--	72	--	34	48	81	--	43
Mayfly	--	338	--	42	--	--	--	76	--	369	--	60	--	178	--	50	--	--	--	47
Caddisfly	26	27	--	--	26	36	--	--	40	--	--	--	8	35	--	--	2	31	--	--

Appendix Table G. Annual stream survey habitat data collected from Pipers Creek reaches over 2006-2009.

Year	Season	Wetted area	Pool area (m^2)	Pool (%)	Units (n)	Pools (n)
Pipers Upper						
2006	Spring	171	78	46	10	4
2006	Summer	140	57	41	8	4
2007	Spring	144	71	50	8	4
2007	Summer	112	46	41	8	3
2008	Summer	102	39	38	8	3
2009	Summer	109	43	43	13	6
Pipers Lower						
2006	Spring	154	100	65	8	5
2006	Summer	176	126	72	7	5
2007	Spring	152	74	49	8	5
2007	Summer	151	67	45	7	4
2008	Summer	166	51	31	9	4
2009	Summer	159	40	40	9	3
Venema Upper						
2006	Spring	73	15	20	9	3
2006	Summer	58	3	6	7	2
2007	Spring	62	7	11	8	3
2007	Summer	56	6	10	7	2
2008	Summer	57	8	14	8	3
2009	Summer	58	0	0	3	0
Venema Lower						
2006	Spring	74	19	25	11	5
2006	Summer	79	29	37	15	7
2007	Spring	66	23	34	14	7
2007	Summer	71	23	33	12	5
2008	Summer	95	21	23	12	6
2009	Summer	69	50	50	11	6
Mohlendorph						
2006	Spring	61	5	8	9	4
2006	Summer	19	3	17	5	2
2007	Spring	42	3	7	5	2
2007	Summer	36	9	24	13	6
2008	Summer	40	5	12	6	3
2009	Summer	37	29	29	12	6

Appendix Table H. Annual streambed particle size data collected at Pipers Creek study reaches from 2006-2010.

Wolman Pebble Count

	Venema Upper				Mohlendorph				Venema Lower				Pipers Lower				Pipers Upper			
	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006	2009	2008	2007	2006
Fines (%)																				
Fall	17	22	10	14	2	6	0	0	10	11	10	3	9	7	8	2	4	2	9	2
Spring	10	20	37	---	3	4	10	---	7	10	11	---	3	18	22	---	3	3	2	---
D50																				
Fall	19	19	19	14	27	19	27	39	39	19	27	27	19	19	14	27	39	27	27	27
Spring	19	27	7	---	27	27	27	---	19	27	14	---	27	14	14	---	19	27	27	---
D84:D50																				
Fall	2.8	2.8	2.0	2.9	2.8	2.0	2.0	1.4	2.0	2.8	2.0	2.0	2.0	2.0	2.9	2.0	2.0	2.0	2.0	2.0
Spring	2.8	2.8	5.7	---	2.8	2.0	2.8	---	2.8	2.8	2.9	---	2.0	2.9	2.9	---	2.0	2.8	2.0	---

Volumetric Sampling

	Venema Upper			Mohlendorph			Venema Lower			Pipers Lower			Pipers Upper		
	2010	2008	2007	2010	2008	2007	2010	2008	2007	2010	2008	2007	2010	2008	2007
Fines (%)															
Fines	2	21	23	1	9	1	3	15	15	2	21	10	2	15	5
Fines	20	25	22	12	20	15	17	23	20	18	24	21	14	21	13
D50															
Surface	38.2	11.3	22.7	65.5	25.7	42.2	53.7	17.3	15.9	29.9	14.2	20.2	22.1	16.6	26.8
Sub-surface	13.6	9.6	25.1	19.6	12.5	14.9	16.4	8.6	11.5	14.1	12.7	12.8	14.8	11.3	19.3
Surface/Sub	2.8	1.2	0.9	3.3	2.1	2.8	3.3	2.0	1.4	2.1	1.1	1.6	1.5	1.5	1.4
D84:D50															
Surface	1.5	2.8	2.1	1.6	2.0	1.6	1.6	5.6	1.9	1.6	2.4	2.1	1.6	2.3	1.9
Sub-surface	3.3	3.3	2.4	2.1	2.4	2.3	3.0	2.9	2.4	2.7	2.6	3.4	1.8	2.5	2.4

Appendix Table I. Monthly minimum, mean, and maximum temperature averages from hourly data recorded at Pipers Creek reaches over 2006-2010. The Mohlendorph logger was discontinued due to dewatering.

	Monthly Temperature (°C)											
	Venema Upper			Venema Lower			Pipers Lower			Pipers Upper		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2007												
Sep	10.39	12.31	13.23	10.20	12.31	14.22	10.83	12.97	16.56	12.00	13.49	15.58
Oct	8.42	10.80	12.24	8.44	10.73	12.41	7.87	10.99	13.10	---	---	---
Nov	6.81	9.35	11.20	6.13	8.94	11.22	5.90	9.07	11.20	---	---	---
Dec	3.56	7.98	10.71	3.35	7.16	10.69	3.49	7.57	10.81	---	---	---
2008												
Jan	5.31	7.37	9.29	4.04	6.38	8.57	4.35	6.77	8.79	---	---	---
Feb	5.75	8.46	10.79	4.95	7.76	10.66	4.98	7.88	10.39	---	---	---
Mar	5.57	8.69	10.96	5.33	8.14	10.76	5.95	8.38	10.44	---	---	---
Apr	6.69	9.28	12.99	5.95	8.84	13.16	6.38	9.19	13.33	---	---	---
May	10.52	11.08	11.83	10.38	11.06	11.94	10.63	11.39	12.36	---	---	---
Jun	10.91	11.44	12.12	10.86	11.50	12.31	11.18	11.95	12.90	---	---	---
Jul	11.86	12.42	13.14	11.96	12.67	13.55	12.40	13.26	14.27	---	---	---
Aug	12.35	12.84	13.58	12.56	13.16	14.09	13.18	13.90	14.88	---	---	---
Sep	11.62	12.35	13.64	11.66	12.47	13.76	12.12	12.99	14.53	---	---	---
Oct	10.34	10.84	11.36	10.15	10.73	11.35	10.60	11.24	11.90	---	---	---
Nov	9.98	10.36	10.75	9.68	10.14	10.58	9.98	10.53	11.07	---	---	---
Dec	7.09	7.60	8.00	6.17	6.74	7.19	6.43	7.16	7.72	---	---	---
2009												
Jan	7.25	7.72	8.14	6.28	6.87	7.43	6.61	7.22	7.79	---	---	---
Feb	7.38	7.95	8.61	6.33	7.18	8.17	6.54	7.39	8.39	---	---	---
Mar	7.57	8.23	9.01	6.49	7.49	8.65	6.65	7.80	9.01	---	---	---
Apr	8.91	9.81	11.19	8.27	9.49	11.25	8.46	9.76	11.66	9.33	9.98	11.59
May	10.28	10.93	11.71	10.03	10.98	12.25	10.30	11.38	12.74	8.80	11.00	13.09
Jun	11.78	12.20	12.69	11.81	12.54	13.58	12.17	13.07	14.25	11.53	13.42	15.27
Jul	12.42	12.87	13.43	12.54	13.29	14.33	13.13	14.01	15.16	12.97	14.52	16.13
Aug	12.42	12.84	13.40	12.59	13.17	14.04	13.18	13.88	14.81	12.98	14.26	15.77
Sep	10.44	11.95	13.91	9.95	11.99	15.20	11.27	10.57	11.39	10.90	12.68	14.31
Oct	9.04	10.96	13.52	8.32	10.89	14.27	11.84	11.27	12.20	5.39	11.08	15.18
Nov	5.87	9.77	11.30	6.23	9.32	11.32	10.37	9.98	10.57	4.97	9.21	12.05
Dec	5.05	7.60	9.93	3.22	6.49	9.58	7.54	7.12	8.15	-1.21	4.62	10.39
2010												
Jan	7.80	9.04	9.76	6.59	8.50	9.68	9.55	9.31	10.00	3.06	7.53	9.88
Feb	7.54	9.17	10.27	6.36	8.64	10.42	9.68	8.89	10.76	1.18	7.09	10.42
Mar	7.57	9.46	11.03	6.38	9.08	11.57	9.29	8.30	10.93	1.24	8.37	12.12
Apr	7.97	9.91	11.81	6.76	9.73	12.73	10.69	10.05	11.78	2.53	8.97	16.30
May	9.04	10.66	12.03	8.37	10.75	13.35	12.50	11.71	13.62	4.87	10.39	14.17
Jun	10.88	11.67	12.63	10.83	11.98	14.31	12.36	11.86	13.33	9.21	12.54	16.56