National Water-Quality Assessment Program

Effects of Urbanization on Stream Ecosystems in the Willamette River Basin and Surrounding Areas, Oregon and Washington

Chapter D of
Effects of Urbanization on Stream Ecosystems in
Six Metropolitan Areas of the United States

Scientific Investigations Report 2006–5101–D

U.S. Department of the Interior
U.S. Geological Survey

Front Cover – Starting lower left corner then clockwise:

Oregon Department of Fish and Wildlife salmon spawning sign at Tickle Creek near Boring, Oregon. (photo by Andy Arnsberg, hydrologic technician, Portland Bureau of Environmental Services, Portland, Oregon, 2004.)
Rainfall runoff along gutter of an impervious street surface, Beaverton. (photo by Hank Johnson, hydrologist, USGS, Portland, Oregon, 2007.)
Urban debris in Johnson Creek at Circle Avenue, Oregon. (photo by Andy Arnsberg, hydrologic technician, Portland Bureau of Environmental Services, Portland, Oregon, 2004.)
Sediment barrier for urban development along Beaverton Creek. (photo by Hank Johnson, hydrologist, USGS, Portland, Oregon, 2008.)

Back Cover – Starting lower left clockwise:

Andy Arnsberg collecting water quality sample at N.F. Deep Creek at Barton, Oregon. (photo by Kurt Carpenter, biologist, USGS, Portland, Oregon, 2004.)
Ian Wigger collecting transducer data at Rock Creek near Vancouver, Washington. (photo by Mike Sarantou, hydrologic technician, USGS, Portland, Oregon, 2004.)
Fanno Creek near Beaverton, Oregon, during a winter high flow event. (photo by Hank Johnson, hydrologist, USGS, Portland, Oregon, 2007.)
Claggett Creek at Keizer, Oregon during summer low flow. (photo by Andy Arnsberg, hydrologic technician, Portland Bureau of Environmental Services, Portland, Oregon, 2004.)

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By Ian R. Waite, Steven Sobieszczyk, Kurt D. Carpenter, Andrew J. Arnsberg,
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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the quality of the Nation's water resources is critical to assuring the long-term availability of water that is safe for drinking and recreation and suitable for industry, irrigation, and habitat for fish and wildlife. Population growth and increasing demands for multiple water uses make water availability, now measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground-water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground-water, and where are those effects most pronounced? By combining information on water-chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities.

From 1991 to 2001, the NAWQA Program completed interdisciplinary assessments in 51 of the Nation's major river basins and aquifer systems, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html). Baseline conditions were established for comparison to future assessments, and long-term monitoring was initiated in many of the basins. During the next decade, 42 of the 51 Study Units will be reassessed so that 10 years of comparable monitoring data will be available to determine trends at many of the Nation's streams and aquifers. The next 10 years of study also will fill in critical gaps in characterizing water-quality conditions, enhance understanding of factors that affect water quality, and establish links between sources of contaminants, the transport of those contaminants through the hydrologic system, and the potential effects of contaminants on humans and aquatic ecosystems.

The USGS aims to disseminate credible, timely, and relevant science information to inform practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
gram (g)	0.03527	ounce, avoirdupois (oz)
kilometer (km)	0.6214	mile (mi)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
meter (m)	3.281	foot (ft)
millimeter (mm)	0.03937	inch (in.)
square centimeter (cm^2)	0.001076	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32.$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datums

Vertical coordinate information is North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is Universal Transverse Mercator (UTM), Zone 10, North American Datum of 1927 (NAD 27).

Elevation, as used in this report, refers to distance above the vertical datum.

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Abbreviations and Acronyms

Abbreviations and Acronyms	Meaning
ADAS	Algal Data Analysis System
ADPS	Automated Data Processing System
AFDM	ash-free dry mass
AhR	aryl hydrocarbon receptor
BOD	biological oxygen demand
CVO	Cascade Volcano Observatory
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon
EPT	Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddesflies)
EUSE	Effects of Urbanization on Stream Ecosystems
H2S	hydrogen sulfide
IDAS	Invertebrate Data Analysis System
NAWQA	National Water-Quality Assessment
NIST	National Institute of Standards and Technology
nMDS	nonmetric dimensional scaling
NWIS	National Water Information System
NWQL	National Water-Quality Laboratory
PAH	polycyclic aromatic hydrocarbons
PCA	principle component analysis
PCB	polychlorinated biphenyls
PTI	Pesticide Toxicity Index
QA	quality assurance
QC	quality control
QMH	qualitative multihabitat
RGS	reporter gene system
ROADDEN	road density
RTH	richest target habitat
SAS	Statistical Analysis Software
SPMD	semipermeable membrane device
SRP	soluble reactive phosphorus
TEQ	toxic equivalent
TN	total nitrogen
TP	total phosphorus
UII	Urban intensity index
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Abstract

This report describes the effects of urbanization on physical, chemical, and biological characteristics of stream ecosystems in 28 watersheds along a gradient of urbanization in the Willamette River basin and surrounding area, Oregon and Washington, from 2003 through 2005. The study that generated the report is one of several urban-effects studies completed nationally by the U.S. Geological Survey National Water-Quality Assessment Program. Watersheds were selected to minimize natural variability caused by factors such as geology, elevation, and climate, and to maximize coverage of different stages of urban development among watersheds. Because land use or population density alone often are not a complete measure of urbanization, a combination of land use, land cover, infrastructure, and socioeconomic variables were integrated into a multimetric urban intensity index (UII) to represent the degree of urban development in each watershed. Physical characteristics studied include stream hydrology, stream temperature, and habitat; chemical characteristics studied include sulfate, chloride, nutrients, pesticides, dissolved and particulate organic and inorganic carbon, and suspended sediment; and biological characteristics studied include algal, macroinvertebrate, and fish assemblages. Semipermeable membrane devices, passive samplers that concentrate trace levels of hydrophobic organic contaminants such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls, also were used. The objectives of the study were to (1) examine physical, chemical, and biological responses along the gradient of urbanization and (2) determine the major physical, chemical, and landscape variables affecting the structure of aquatic communities.

Common effects documented in the literature of urbanization on instream physical, chemical, and biological characteristics, such as increased contaminants, increased streamflow flashiness, increased concentrations of chemicals, and changes in aquatic community structure toward a more tolerant community associated with organically enriched conditions, generally were observed in this study. The strongest correlations to the UII and to many of the algal, macroinvertebrate, and fish assemblage metrics and community ordination involved water-chemistry metrics including the total pesticide concentration, toxic equivalents (extract assay from semipermeable membrane devices), and dissolved oxygen. Hydrologic variability metrics, such as flashiness, that normally are considered to be one of the main processes of urban disturbance had a strong association to the algal and fish assemblages in this study; however, the hydrologic variables for macroinvertebrates were secondary to the water-chemistry metrics mentioned above. Generally, the high urban intensity sites had high abundances of eutrophic and lower dissolved oxygen-indicating diatoms, high abundances of noninsects and tolerant insects, and high abundances of nonnative fish species. On the other hand, the low urban intensity sites had higher abundances of pollution sensitive diatoms, larger numbers of the sensitive macroinvertebrate EPT taxa (Ephemeroptera, Plecoptera and Trichoptera Orders), and fish assemblages with higher abundances of sensitive salmonids. The percent salmonid and macroinvertebrate EPT richness metrics plotted against the UII indicated a possible threshold response at about 25 on the UII, which is equivalent to an impervious surface value of about 5 percent. However, due to the added agricultural land use at sites within the 25 to 60 UII range, this possible threshold probably is not solely due to urbanization, but a combination of urban and agricultural land use. The effects of agricultural and urban land use could not be distinguished from each other, yet combined they provide a good assessment of overall watershed disturbance.

Introduction

Research has shown that stream ecosystems are increasingly degraded by urban development and human population growth (Booth and Jackson, 1997, Paul and Meyer, 2001; Walsh and others, 2005; Tate and others, 2005). The growth of urban areas changes landscapes and increases stresses to freshwater systems by adversely altering water-quality, habitat, biodiversity, and ecosystem processes (McDonnell and Pickett, 1990; Sala and others, 2000; Paul and Meyer, 2001; Brown and others, 2005; Sprague and others, 2006). Urban growth, or urbanization, is defined as the development of rural, agricultural, or forested land into urban land, such as buildings and roads. Urbanization may be further defined by incorporating population density estimates, percentages of urban land use classification from remote sensing data (Brown and others, 2005; Tate and others, 2005), or percentage of impervious surface cover (Arnold and Gibbons, 1996). Regardless of how urbanization is characterized, it directly changes the physical habitat and stream hydrology of a river system (Sinokrot and Stefan, 1993; LeBlanc and others, 1997). For example, encroachment of urban land into riparian areas decreases canopy cover, allowing more solar radiation to heat streams (Waite and Carpenter, 2000; Jacobson and others, 2001; Sprague and others, 2006). The expansion of urban land also introduces more industrial and human waste to rivers, which combines with more urban and agricultural pesticide applications that deteriorate water quality in streams. Additionally, urbanization brings increased development and more impervious surfaces. Impervious surfaces, such as roads, parking lots, and rooftops, increase surface runoff volumes and reduce the amount of water that infiltrates into the soil and ground water. As a result, the excess runoff modifies stream hydrology and channel morphology causing the degradation of aquatic habitats (Winterbourne and Townsend, 1991), the increase in sedimentation rates (Waite and Carpenter, 2000), and a greater fluctuation in frequency and magnitude of stormflows.

To investigate the effect of multiple urban stressors on stream ecosystems, the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Effects of Urbanization on Stream Ecosystems (EUSE) study examined the effects of varying degrees of urbanization among various watersheds in the Willamette River basin and surrounding area. The approach integrated multiple parameters, such as socioeconomic variables, population statistics, and land use metrics, into a single index measurement of urbanization intensity (Cuffney and others, 2000; Tate and others, 2005), and was based on a common design and sample collection technique (McMahon and Cuffney, 2000). Using this multimetric indicator of urban intensity, 28 watersheds in the study area were selected with increasing degrees of urbanization (table 1). The urban land use gradient ranged from minimal urban development to highly developed land, while limiting differences in natural features and local disturbances. The gradient was used to assess the effects of urbanization on stream water chemistry, habitat, and biological conditions (Walsh and others, 2001; Fitzpatrick and others, 2004; Sprague and others, 2006).

Purpose and Scope

This report describes the physical (stream hydrology, water temperature, and stream habitat), chemical (nutrients and pesticides), and biological (algae, macroinvertebrate, and fish assemblages) characteristics of stream ecosystems in 28 watersheds along a gradient of urbanization in the Willamette River basin and surrounding area of Oregon and southwestern Washington from 2003 through 2005. Watersheds were selected to minimize natural variability between sites due to watershed size, elevation, and climate, and to maximize coverage of different degrees of urban development. The objectives of the study were to (1) examine physical, chemical, and biological responses along a gradient of urbanization and (2) determine the major physical, chemical, and landscape variables associated with aquatic communities.

Study Area

The Willamette River basin and surrounding area includes 35,000 km^2 in northwestern Oregon and southwestern Washington (fig. 1). Although the Willamette River basin is in Oregon, the study area was extended into Washington because of similar socioeconomic, climatic, ecologic, and topographic settings. For example, 1,000 km^2 of the Willamette Valley-Level III ecoregion, as defined by Omernik (1987) extends across the Columbia River into Washington (fig. 2). An ecoregion—unlike a watershed, which delineates an area of convergent drainage—denotes an area of shared natural characteristics, such as soil types, elevation, and climate. The Willamette Valley ecoregion contains a mixture of rolling prairies, mixed forests, and extensive lowland valley wetlands.

Land cover in the basin (fig. 3) is predominately forest (66 percent), with moderate agriculture (29 percent) and minimal urban (3.5 percent) and surface water (1.5 percent) (U.S. Geological Survey, 2005). The valley plains and foothills primarily are used for cultivated crops, pasture, and grasslands, although minimally developed areas, such as Dundee, Oregon, to highly developed urban areas, such as Portland, Oregon, also are in the valley. Fertile soils and a temperate climate

Table 1. Land cover and other watershed characteristics for 28 streams sampled during the urbanization gradient study, Willamette River basin and surrounding area, Oregon and Washington.

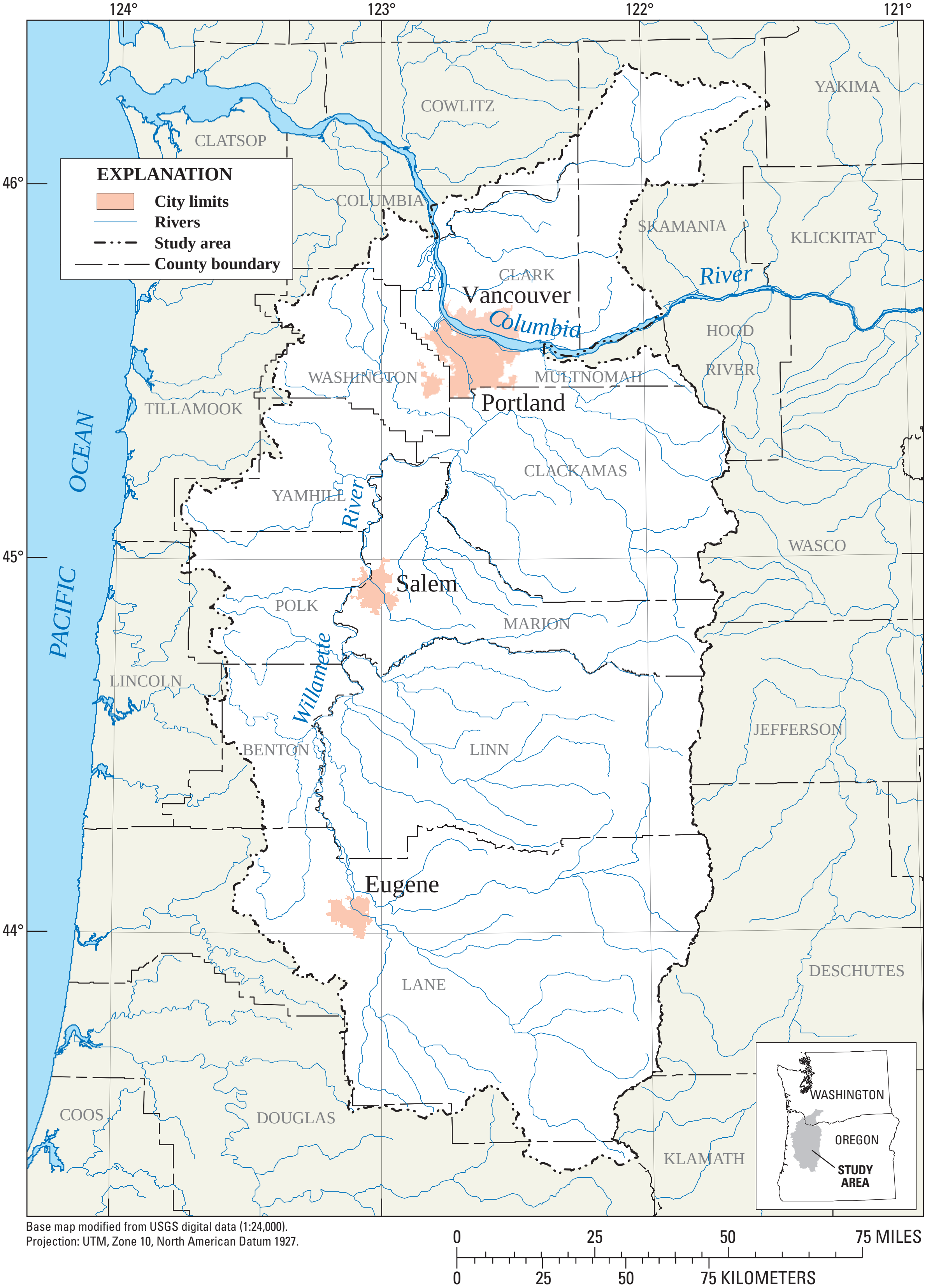
[See figure 4 for site locations. Sites are sorted by urban intensity index (UII). Shading represents low, medium, high, and very high UII scores. **Abbreviations:** km^2, square kilometer; USGS, U.S. Geological Survey; SW, southwest; OR, Oregon, WA, Washington]

Site identification No.	Site name	USGS station No.	Area (km^2)	Urban intensity index	Urban (percent)	Agriculture (percent)	Mean impervious surface (percent)
1	Beaverton Creek near SW 216th Avenue, near Orenco, OR	14206435	96	**100**	83	1	40
2	Claggett Creek at Keizer, OR[1]	450022123012400	25	**100**	98	0	55
3	Fanno Creek at Durham, OR	14206950	81	**96**	84	1	39
4	Pringle Creek at Salem, OR[1]	445551123015800	25	**88**	89	6	42
5	Kellogg Creek at Milwaukie, OR[1]	452526122364400	34	**88**	81	2	39
6	Amazon Creek near Danebo Road, at Eugene, OR	440257123103200	50	**77**	62	8	29
7	Tryon Creek below Nettle Creek, near Lake Oswego, OR	14211315	17	**72**	60	0	23
8	Curtin Creek near Vancouver, WA	454321122352300	30	**69**	72	16	29
9	Johnson Creek at Circle Avenue, OR	452912122291200	56	**59**	42	24	17
10	Battle Creek near Turner, OR	445029122592600	30	**58**	33	40	13
11	Rock Creek at Quatama Road, near Hillsboro, OR	14206347	67	**51**	28	26	13
12	Whipple Creek near Salmon Creek, WA[1]	454510122424900	22	**49**	38	19	14
13	Chicken Creek near Sherwood, OR	14206750	40	**45**	22	36	9
14	North Fork Deep Creek at Barton, OR[1]	452337122243500	37	**39**	27	48	10
15	Oak Creek at Corvallis, OR	443326123165200	33	**39**	7	19	3
16	Tickle Creek near Boring, OR[1]	452414122213200	34	**32**	19	34	8
17	Chehalem Creek at Newberg, OR	451734122585400	98	**29**	9	44	3
18	Silk Creek near Cottage Grove, OR	434745123040200	42	**24**	3	11	1
19	Rock Creek near Battleground, WA[1]	455122122310600	26	**23**	8	7	2
20	Salmon Creek near Battleground, WA[1]	454549122295800	59	**20**	13	2	3
21	Deep Creek near Sandy, OR[1]	452231122200000	31	**17**	4	30	1
22	Nate Creek near Colton, OR	14199710	29	**15**	2	12	1
23	Milk Creek at Camp Adams, OR	450955122291200	104	**12**	2	9	1
24	South Scappoose Creek at Scappoose, OR	454543122524900	65	**8**	3	3	1
25	North Yamhill Creek near Yamhill, OR	452149123194900	66	**8**	1	0	0
26	Lost Creek near Dexter, OR	435212122483300	83	**6**	0	1	0
27	Iler Creek near Forest Grove, OR	453506123125700	13	**4**	0	5	0
28	East Fork Dairy Creek near Meacham Corner, OR[1]	14205400	88	**0**	1	1	0

[1] High frequency sampling sites, which spanned the full range of the UII, were used to determine whether the degree of urbanization affected the seasonality of water chemistry.

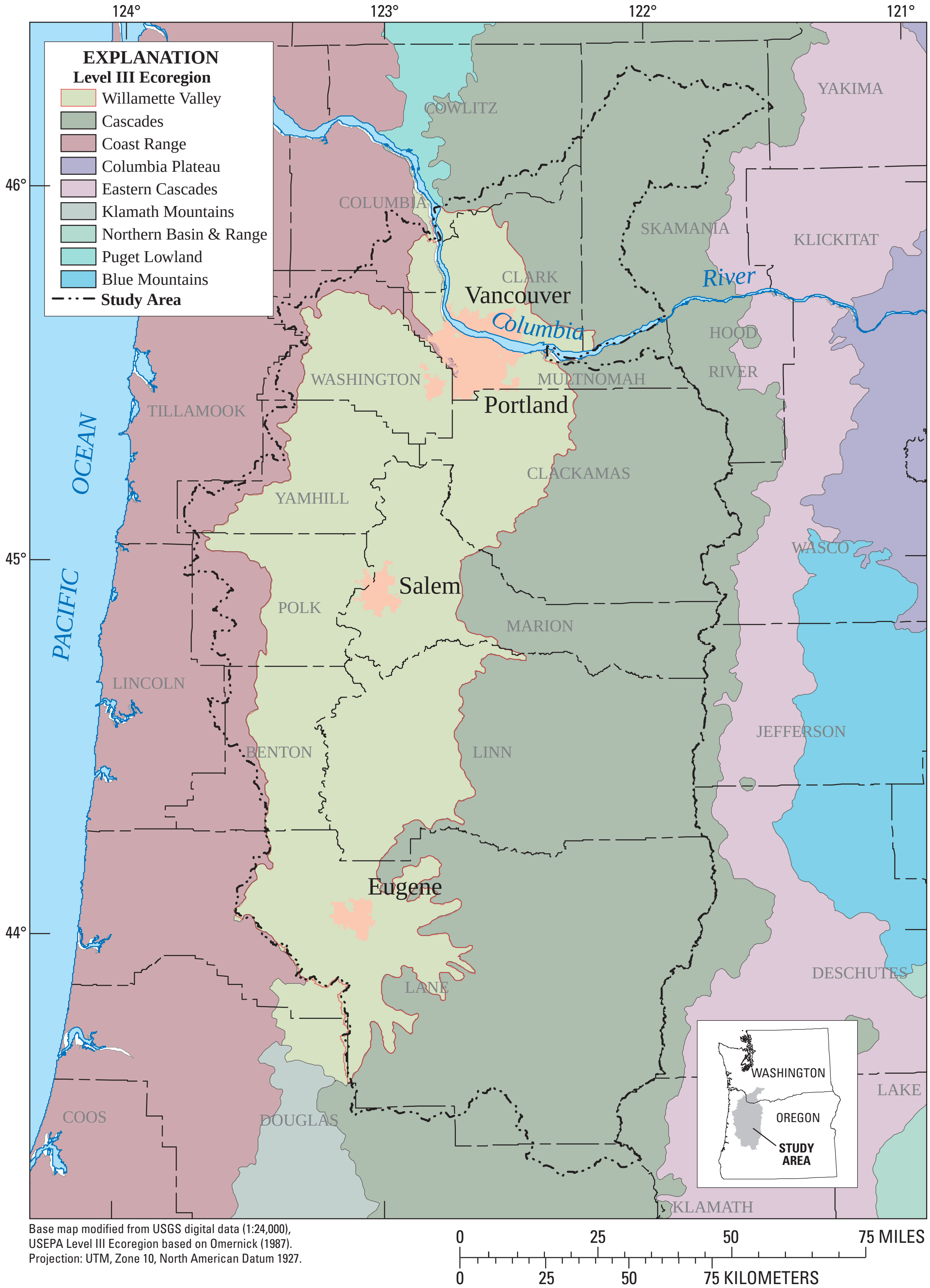
make the Willamette Valley a thriving agricultural region (Thorson and others, 2003). Land use in the forested Coastal Range and Cascades is a combination of timber harvesting, recreation, and development. Centered on the confluence of the Columbia and Willamette Rivers, Portland is the most populous city in Oregon, with 539,000 people in city limits and nearly 3 million people in the Portland/Salem/Vancouver metropolitan area (U.S. Census Bureau, 2000). The population in the metropolitan area increased almost 30 percent from 1990 to 2000, with some suburban populations increasing more than 80 percent during the same period (U.S. Census Bureau, 2000).

With temperate, dry summers and cool, wet winters, the Willamette River basin and surrounding area is characteristic of Pacific Northwest climate. About 90 percent of the annual precipitation occurs during October through May (Uhrich and Wentz, 1999), falling as rain in the valley and snow in the mountains. The drainage network in the Willamette Valley combines natural dendritic tributaries, complex networks of canals in agricultural areas, and sewer piping in cities. Dams and reservoirs regulate most large rivers, such as the McKenzie, Santiam, and Willamette Rivers, which supply drinking water, power generation, and irrigation to different parts of the region.



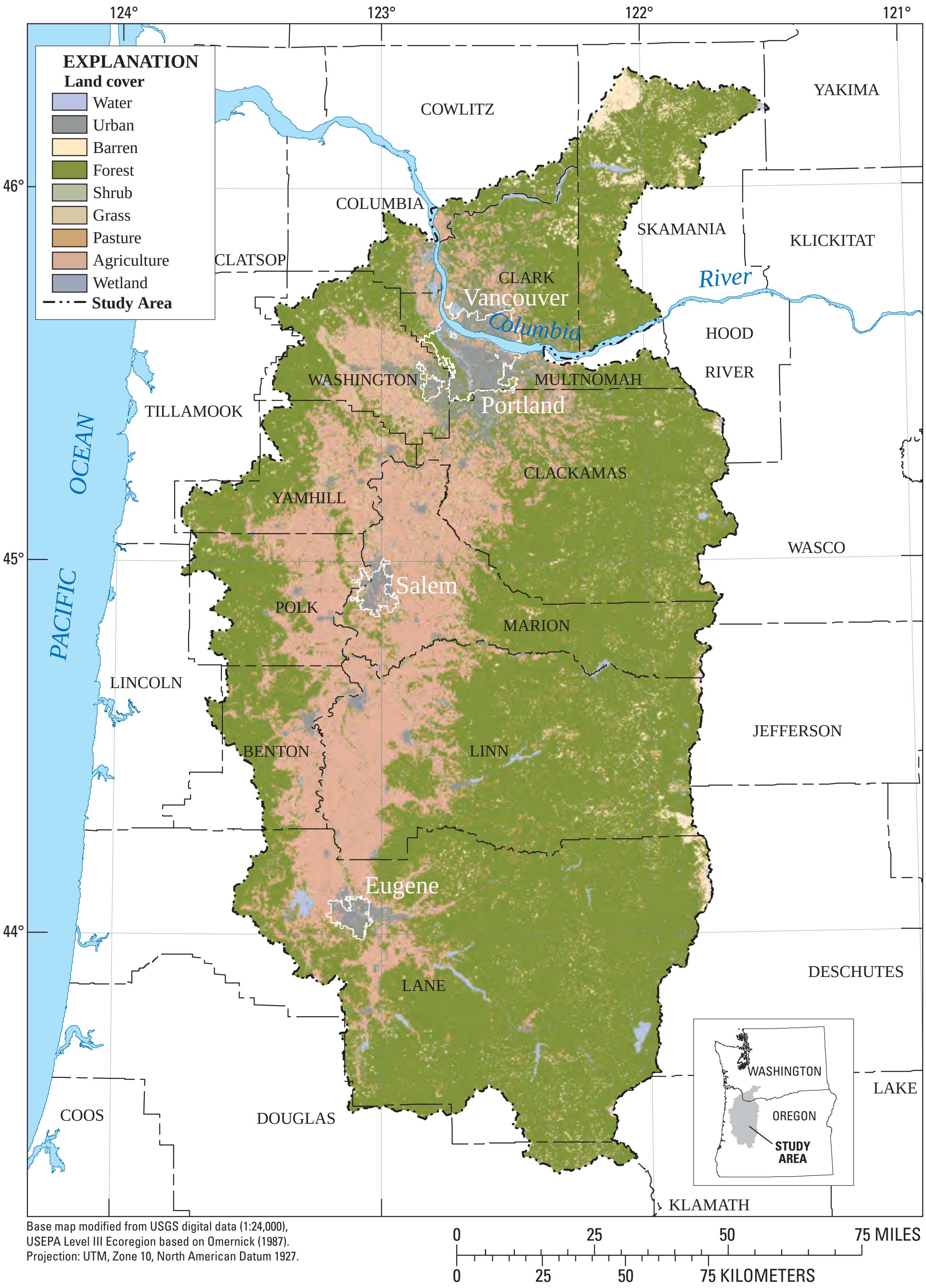
Base map modified from USGS digital data (1:24,000).
Projection: UTM, Zone 10, North American Datum 1927.

Figure 1. Location of the Willamette River basin and surrounding area, Oregon and Washington.



Base map modified from USGS digital data (1:24,000),
USEPA Level III Ecoregion based on Omernick (1987).
Projection: UTM, Zone 10, North American Datum 1927.

Figure 2. Level III ecoregions of the Willamette River basin and surrounding area, Oregon and Washington.



Base map modified from USGS digital data (1:24,000),
USEPA Level III Ecoregion based on Omernick (1987).
Projection: UTM, Zone 10, North American Datum 1927.

Figure 3. National land cover data, Willamette River basin and surrounding area, Oregon and Washington, 2001 (U.S. Geological Survey, 2005).

Methods

Methods used during this study followed guidelines established for the National EUSE Program (Cuffney and others, 2000; McMahon and Cuffney, 2000; Tate and others, 2005). Site selection started with an initial 206 "candidate" streams and was eventually refined to 28 "final" streams. Data collection began in November 2003 and continued through March 2005, with the 28 final streams sampled for physical habitat, water chemistry, and aquatic biology. The final streams, and their associated watersheds, represented varying degrees of urbanization, yet shared similar geospatial and socioeconomic characteristics. During the study, 96 water-quality samples were collected and stream habitat was evaluated at each site. In addition, the biological community (algae, benthic macroinvertebrates, and fish) in each stream was sampled during low-flow conditions. Stream stage and water temperature were monitored in each stream from March through November 2004. Semipermeable membrane devices were installed at each location for about one month.

Site Selection

Streams selected for this study represented a full gradient of urbanization, and met the predefined geospatial and ecological characteristics developed for the National EUSE Program defined below.

Geospatial and Ecological Characteristics

To limit natural variability between watersheds, certain geospatial and ecological constraints were required. The two primary site selection constraints were "watershed size" and "percent coverage in the Willamette Valley-Level III Ecoregion (Omernik, 1987)". Watersheds could cover no less than 10 km^2 and not exceed 130 km^2. Additionally, all watersheds included a minimum of 20 percent of the Willamette Valley ecoregion. With these guidelines, site selection and watershed processing proceeded using Geographic Information Systems (GIS) and the USGS National Elevation Dataset (30-m resolution NED). An initial 206 candidate sites were identified and respective watersheds were delineated (fig. 4). Several GIS datasets were processed against the candidate watersheds, producing an assortment of land cover variables for each site. The GIS datasets included layers of socioeconomic (census variables), climatic (precipitation), ecologic (ecoregion), topographic (slope), hydrologic (hydrologic landscape regions), infrastructural (census road variables), and soil characteristics (erosion potential), which were calculated for (1) the entire basin, (2) the proximate segment of the upstream area, and (3) the adjacent riparian area (appendix A, table A1). For more detailed descriptions of techniques, conversions, and guidelines, as well as a complete list of geospatial variables and their descriptions, refer to Sprague and others (2006) and Falcone and others (2007).

Gradient in Degree of Urbanization

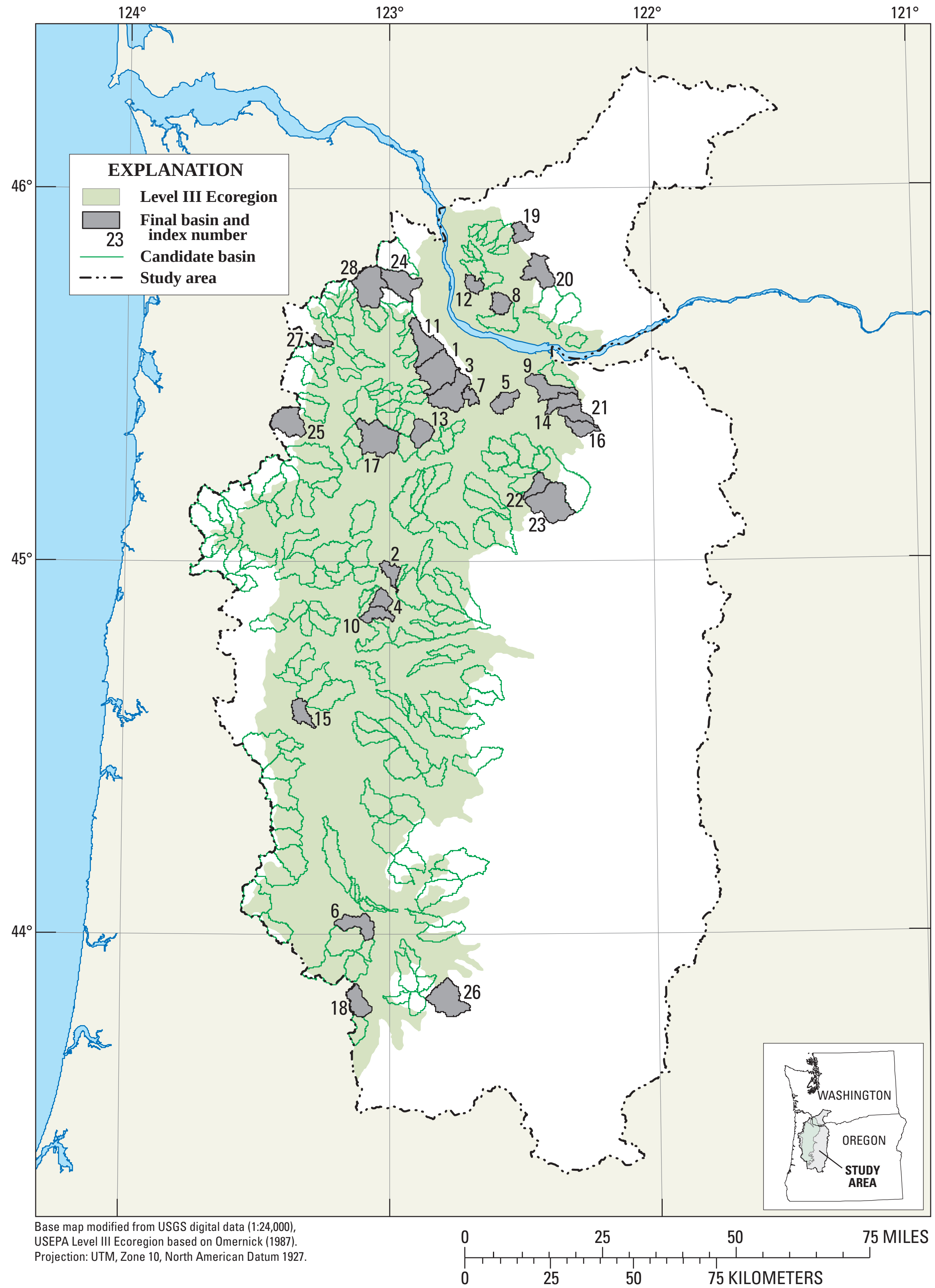
The main objective of this study was to examine the effect of different degrees of urbanization on stream ecosystems. Rather than investigate long-term temporal changes in one system, this study monitored a large number of sites at progressively higher levels of urbanization in a short timeframe. Theoretically, the relation of multiple sites at increasing degrees of urbanization should mimic similar development of one site over progressive years of increasing urbanization (Sprague and others, 2006). Therefore, selecting watersheds that represented a range in urbanization from minimum development to maximum development was paramount.

Classifying urbanization was more complicated than basing it solely on urban land use. For this study, watershed and riparian land cover, infrastructural, and demographic variables were integrated into a "candidate" urbanization intensity index (UII) (McMahon and Cuffney, 2000). This UII was calculated from data for all 206-candidate watersheds. Seventeen GIS variables with at least a 0.5 Spearman's correlation to population density and that were not correlated above 0.5 with watershed size were included in the calculation. After the UII was generated, 70 of the 206 watersheds were selected for reconnaissance.

Site Accessibility

Each of the 70 remaining candidate sites were visited after their watersheds were delineated, characterized, and ranked with a UII. Field reconnaissance was used to verify GIS results and to evaluate accessibility and safety restrictions. Some sites were relocated upstream or downstream of the original location to obtain reaches with cobble or riffle substrate, or to avoid culverts or other undesirable obstacles. Some sites were excluded because the stream was ephemeral, watershed conditions were impossible to survey, or landowners would not permit access. Whenever possible, sites were selected to provide an even distribution along the UII.

Of the remaining candidate sites, a prerequisite 30 final sites were selected throughout the Willamette River basin and surrounding area. Initially, all 30 watersheds met the required geospatial and ecological characteristics. However, after adjustments for accessibility were incorporated into the drainage delineation, two sites did not fulfill the 20 percent coverage of the Level III ecoregion requirement—South Scappoose Creek in Oregon (6 percent) and Rock Creek in



Base map modified from USGS digital data (1:24,000), USEPA Level III Ecoregion based on Omernick (1987). Projection: UTM, Zone 10, North American Datum 1927.

Figure 4. Candidate and final watersheds selected for the urban gradient study, Willamette River basin and surrounding area, Oregon and Washington.

Washington (17 percent). The sites remained in the study after analysis of land cover, topographic, and hydrologic characteristics revealed that the watersheds shared similar characteristics with the other 28 sites and were necessary to fill vacancies in the urbanization gradient. Two other sites were eventually eliminated late in the study because conditions were not favorable for biological sampling in summer after water chemistry samples had been collected the previous winter. The final 28 sites and their basic watershed characteristics are listed in table 1.

Urban Intensity Index

A “final” UII was generated and applied to the 28 final sites based on the procedure developed by McMahon and Cuffney (2000). To calculate the final UII, a select group of 24 input GIS variables (table A2) were normalized to watershed area and then sorted by ascending variable percentage. The sorted values then were ranked on a scale of 0 to 100. Variables that correlated with population density (according to a criterion of a Spearman’s rank correlation of greater or equal to 0.70) and remained uncorrelated with watershed area (absolute value of Spearman’s correlation less than or equal to 0.50) were used as inputs for the UII. For each site, all ranked GIS variables that met these constraints were averaged to produce a raw UII. The averaged raw values then were scaled from 0 to 100. The resulting value represented the final urban intensity index value for each site. The final UII differed from the candidate UII because fewer sites were factored into the analysis, different GIS variables were incorporated into the UII calculation, and a higher Spearman’s rank correlation was used (increased from 0.50 from 0.70).

Data Collection

Physical Characteristics

Stream Hydrology

Stevens-Greenspan Model PS310 pressure transducers, each with an internal data logger, were used to measure stream-stage fluctuation during the study (Greenspan Technology, 2006). Transducers were placed instream in pools or runs to ensure consistent response of hydrologic stage and to minimize the potential for dewatering. The transducer model was not vented to the atmosphere; therefore, changes in recorded pressure reflected changes in stream level and atmospheric pressure. Data were corrected for fluctuations in atmospheric pressure using hourly barometric pressure data from nearby airports because continuous barometric pressure records were not available at the study sites. The stage data from the transducers had a precision of ±0.036 m, which did not meet USGS requirements for stage data precision (±0.003 m) (Sauer, 2002); however, it was deemed acceptable for the purposes of this study.

For logistical reasons, the pressure-transducer deployment periods varied among the sampling sites, with the most complete record obtained between March and November 2004. This 9-month period included a number of “typical” spring and autumn rain events, and provided adequate data to characterize the hydrologic variability among sites. Hydrologic variables calculated from the stage data included more than 35 hydrologic variables. These variables included measures of stage variability (regularity in streamflow), estimates of streamflow magnitude (amount of water moving past a given point per unit of time), stream flashiness (how quickly streamflow changes from one magnitude to another), duration (length of time associated with specific streamflow conditions), and frequency (how often streamflows greater than or less than a certain magnitude recur). Calculations were based on equations outlined in McMahon and others (2003) using SAS version 8 (Delwiche and Slaughter, 1998).

Stream Temperature

Stevens-Greenspan Model PS310 pressure transducers also monitored continuous water temperature data (30-minute intervals) during the study. Twenty percent of the transducers were tested for accuracy (within ± 0.01°C, verified by comparing readings in a temperature bath with a traceable National Institute of Standards and Technology [NIS] thermometer prior to field deployment). Temperature data were stored in the Automated Data Processing System (ADAPS), a part of the National Water Information System (NWIS) (U.S. Geological Survey, 2003). Summary statistics for various water temperature measures included daily minimum, maximum, mean, range, and standard deviation, which were calculated for each stream using hourly data.

Occasionally, short periods of temperature record were lost due to transducer failure or dewatering, such as when stream levels dropped during low flow in late summer. Temperature data for the missing intervals were reconstructed using an extraction-correlation technique, which used the 30-minute data to extract daily mean values from March through November 2004 data. Sites then were correlated with each other. Linear regressions based on these correlations were used to estimate temperature values for days without a daily mean value. At sites with missing data, an average of the regressions was used to estimate missing values.

Watershed and Stream Habitat

Watershed-level characterization of habitat provided information on the upstream geologic, climatic, hydrologic, morphologic, and biologic influences at a site. Watershed-level habitat variables defined in this study included drainage area, drainage density, watershed length, mean watershed elevation, drainage shape, watershed relief, drainage texture, and cumulative perennial stream length. Other watershed-level information included land cover, surficial geology, soil, and riparian variables. Segment-level characterization of habitat provided information on finer scale influences in the relatively homogenous segment stream length. Actual segment length varies among streams depending on the distance between significant tributaries and/or point source inputs (Fitzpatrick and others, 1998). Segment-level variables determined in this study included sinuosity, slope segment length, and channel gradient. Watershed-level and segment-level characteristics were derived by GIS.

Reach-level characterization based on site visits was the principal means for describing local-scale influence within a segment (Fitzpatrick and others, 1998). Reach length was determined by multiplying the mean wetted channel width by 20 to ensure that all habitat types (pools, riffles, and runs), were represented within the reach. Reach-scale habitat data were collected during low-flow conditions in July and August 2004. Stream depth, width, bed substrate, habitat cover, bank morphology, canopy closure, stream velocity, and bank vegetation were measured at 11 or 12 equally spaced transects along each reach (mesoscale characterization). At one site—Curtin Creek—only nine transects were completed due to channel reach constraints. In addition, point velocity, substrate, and depth were measured where richest targeted habitat algae and benthic macroinvertebrate samples were collected (micro-scale characterization). A complete list of habitat variables used in this study is given in the appendix (tables A3 and A4). Detailed information on methods of habitat data collection and variables is available in Fitzpatrick and others (1998).

GIS variables, additional to those originally used in site selection and UII genesis, were gathered for analytical purposes. Hydrologic variables describing stream segment, riparian buffer, and road/stream intersection were examined, as well as associated dams, reservoirs, and waterway diversions. In addition, the program FRAGSTATS (McGarigal and others, 2002) was run for each final watershed to evaluate spatial land use patterns. FRAGSTATS variables quantified the degree of fragmentation, such as size, configuration, and connectivity, of urban and nonurban areas in a watershed (Sprague and others, 2006). As Alberti and Marzluff (2004) noted, this disruption of continuous land can affect ecosystem health by limiting or interrupting the natural movement of organisms. All additional GIS variables are available in Sprague and others (2006).

Chemical Characteristics

Discrete Samples

Water samples for chemical analysis were collected from all 28 sites twice during the study. Samples were collected from all sites in May 2004 (spring sampling) and in late August or early September 2004 (summer sampling) to bracket the biological sampling during July through September 2004. Water-chemistry conditions during these months were more likely to have a more direct effect on the biological communities in the streams than conditions earlier in the study. To document the seasonal variability in water chemistry, 10 of the 28 sites were sampled 4 additional times: November 2003, and January, March, and June 2004. These 10 “high frequency” sampling sites spanned the full range of the UII to determine whether the degree of urbanization affected the seasonality of water chemistry (table 1).

Sulfate, chloride, nutrients, pesticides, dissolved and particulate organic and inorganic carbon, and suspended sediment samples were collected at all sites (table A7). Field measurements of water temperature, dissolved oxygen (DO), pH, specific conductance, and streamflow also were made during sampling. Samples were collected using standard protocols as outlined in the USGS National Field Manual (U.S. Geological Survey, variously dated). Nutrient and pesticide samples were analyzed at the USGS National Water-Quality Laboratory (NWQL) in Lakewood, Colorado, using methods developed by Fishman (1993) and Zaugg and others (1995). Suspended-sediment samples were analyzed at the USGS Cascade Volcano Observatory (CVO) sediment laboratory in Vancouver, Washington. Quality-control samples, including field blanks, replicates, and laboratory spikes were collected throughout the study and analyzed at the NWQL and CVO. About 10 percent of the total number of field samples was collected for quality assurance. All quality-control, or quality-assurance, samples analyzed indicated that sample collection, processing, or laboratory analysis were acceptable.

Semipermeable Membrane Devices

Semipermeable membrane devices (SPMDs) are passive sampling cartridges that were deployed in each stream to sample and concentrate hydrophobic organic contaminants from the water (Huckins and others, 1993; Bryant and others, 2007). In this study, SPMDs were designed to mimic the fatty tissues of fish, and used to indicate the potential for bioaccumulation of polychlorinated dioxins and furans, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine and pyrethroid insecticides.

SPMDs were deployed in each of the 28 streams for about 4 weeks beginning in July 2004. At the end of the deployment period, they were removed and sent to multiple locations for analysis. Contaminant residues were recovered and separated at Environmental Sampling Technologies in St. Joseph, Missouri, as described in Huckins and others (1990). An ultraviolet fluorescence scan to quantify total PAHs (Johnson and others, 2004) and a Microtox® bioassay (Johnson, 1998) was run at the USGS Columbia Environmental Research Center in Columbia, Missouri. U.S. Army Corp of Engineers environmental laboratory in Vicksburg, Mississippi, ran an additional assay, the P450 RGS test that screens for aryl hydrocarbon receptor (AhR) type compounds that include PCBs, PAHs, dioxins, and furans (Murk and others, 1996).

Because SPMDs integrate chemical conditions over time and, sometimes, during variable flow conditions, they provide a more complete representation of chemical exposure than periodically collecting water samples (Huckins and others, 1993). SPMDs also eliminated the problem of determining chemical exposure in aquatic organism tissue by eliminating concern whether organisms metabolized compounds or if organisms migrated from exposure sources. Limitations of the SPMDs include:

1. The inner dialysis tubing (dialysate) was permeable only to nonionic compounds; and
2. The accumulation rates may have been affected by the physicochemical properties of individual nonionic compounds, variations in water temperature, flow velocity, and biofouling on the exterior membrane surface (Huckins and others, 1993) and the exposure duration.

All final data used in analysis were blank corrected/time normalized according to procedures outlined by Bryant and others (2007) to address these limitations and allow for better comparability of data among sites.

Biological Characteristics

Algal, benthic macroinvertebrate and fish assemblage samples were collected once during the study period in each of the 28 streams following protocols described in Moulton and others (2002). Algal and benthic macroinvertebrate samples were collected during September and October 2004, respectively, and fish communities were sampled in July and August 2004.

Algal Assemblages

Quantitative algal samples were collected at each site from riffles at the richest targeted habitat (RTH) using methods described in Moulton and others (2002). RTH algal samples were collected from 5 to 15 representative rocks per site and combined into a single sample. Rocks were removed, and algal material was collected using the pipe-scribe top rock scrape method described in Carpenter (2003). A round plastic scribe (short length of PVC pipe) with an outside diameter ranging between 4 and 10.4 cm was placed on each rock, and algal material outside the scribe was removed with a plastic-bristle brush or scraped off with a knife, and discarded. The circular patch of algae remaining on the rock was scraped into a small washbasin, and rinsed into a 1-L sample bottle using stream water. Samples were briefly homogenized with an electric blender, and subsamples were collected for chlorophyll-*a*, ash-free dry mass (AFDM), and species identification. Chlorophyll-*a* and AFDM subsamples were collected on 45-micron glass-fiber filters, wrapped in foil, sealed, packed on dry ice, and shipped to the NWQL for fluorometric chlorophyll-*a* (Arar and Collins, 1997) and gravimetric AFDM analyses (Britton and Greeson, 1987). All algae water samples were preserved in 5 percent buffered formalin solution and shipped to the Academy of Natural Sciences of Philadelphia for taxa identification and enumeration following protocols described by Charles and others (2002).

Benthic Macroinvertebrate Assemblages

One semiquantitative RTH sample for benthic macroinvertebrates was collected from five riffle areas in each stream. Each of the five subsamples were collected using a 500-micron mesh Slack sampling net (modified Surber design), which was placed in the stream, and rocks were cleaned of benthic organisms from a 0.25 m^2 sampling area into the net. The five subsamples were combined in the field at each site. Additionally, one qualitative multihabitat (QMH) sample was collected using a 500-micron mesh dip net, which was used to collect and composite organisms from a diversity of microhabitats present at each site (for example, riffles, runs, pools, grasses, woody debris) into a 19-L bucket. Microhabitats were sampled equally for a maximum of 1 hour. Both individual sample types underwent a field elutriation process to clean and remove large organic debris, excess rocks, and sand. The composited macroinvertebrate sample was transferred into a 1-L plastic bottle, preserved with 10 percent buffered formalin, and shipped to the NWQL for taxa identification and enumeration (Moulton and others, 2002).

Fish Assemblages

Fish were collected using a Smith-Root Model BP2 backpack electro-shocker, with two separate upstream passes from the start to the end of the reach. Fish were caught using 6 mm mesh nets and stored in aerated live wells. All fish were identified and enumerated in the field after each sampling pass. The first 30 fish of each species were weighed to the nearest 0.1 g, measured to the nearest millimeter, and checked for external anomalies (Moulton and others, 2002). The remaining individuals of each species were enumerated and checked for anomalies. Representative specimens of difficult to identify species were labeled and preserved in 10 percent buffered formalin solution and sent to the Department of Fish and Wildlife Ichthyology Museum at Oregon State University, Corvallis, Oregon, for identification verification.

Data Reduction and Analysis

Pesticide Toxicity Index Calculations

To supplement the spatial comparison of individual pesticides among sites, a pesticide toxicity index (PTI) was calculated for each stream water sample (Munn and Gilliom, 2001). An additive model was used with the PTI to estimate potential toxicity of a water sample containing more than one pesticide. The toxicity was estimated by comparing stream concentrations to laboratory bioassay test endpoints such as the Lethal and Effect Concentrations for 50 percent of a test population (LC_{50} and EC_{50}, respectively) for three taxonomic groups of aquatic organisms (fish, benthic invertebrates, and cladocerans [water flea]) (Munn and others, 2006). Although the PTI does not determine the actual toxicity of a sample, it can be used to estimate and rank the relative toxicity of samples containing one or more pesticides. The PTI value was computed for each sample by summing the toxicity quotients (the measured concentration of a pesticide in a stream sample divided by its median toxicity concentration from bioassay tests) for all pesticides detected in a sample. Some pesticide compounds had no toxicological data for some or all of the three taxonomic groups. To maximize the number of pesticides included in the PTI, a single overall PTI was calculated using the most sensitive or lowest median toxicity concentrations for fish, benthic macroinvertebrates, and cladocerans. Limitations of the PTI include:

1. PTI was based on an additive model of pesticide toxicity (using combined toxicity-weighted concentrations of pesticides from multiple chemical classes without regard to mode of action), so the actual toxicity is not known because chemicals may act additively (3+2+1=6), independently (not additively, 1+1+1+1=1), or synergistically (3+2+1=9);

2. PTI values were based on laboratory experiments (toxicity bioassays) of acute exposure that do not account for potential effects from repeated or chronic exposure. Environmental factors that may have affected bioavailability and toxicity, such as dissolved organic carbon (DOC) and temperature, were not incorporated into the PTI;

3. PTI was calculated for pesticides in samples taken from the water column, which may underestimate the toxicity from pesticides that accumulate in benthic sediments. This is especially true for hydrophobic compounds with moderate or high K_{oc} values (for example, organophosphate insecticides or pyrethroid insecticides;

4. In some cases, the toxicity endpoint was based on a few, or in some cases just 1 laboratory test (the number of tests for an individual pesticide and taxonomic group ranged from 1 to 165); and

5. PTI values were calculated for just the three groups of aquatic organisms, not the full spectrum of aquatic life in these streams.

Despite its limitations, the PTI proved to be a useful measure for assessing the potential cumulative effects of pesticide on aquatic ecosystems, and for examining the relative toxicity of pesticides that do not currently have aquatic-life benchmarks.

Explanatory Environmental Variables

Five distinct environmental data sets were compiled, which included hydrology, water temperature, stream habitat, water chemistry, and watershed characteristics. These data sets were used to explain differences in algae, benthic macroinvertebrates, and fish at the 28 sites. Generally, the number of variables in each data set greatly exceeded the number of sampling sites (n = 28); therefore, a large number of variables in each data set had to be eliminated with the remaining variables transformed and standardized to meet important statistical assumptions of normality and homogeneity of variance (Legendre and Legendre, 1998; Clarke and Gorley, 2006). The number of variables in each data set was reduced by analyzing the correlation matrix and scatter plots to eliminate strongly correlated, redundant variables. Appendixes in Sprague and others (2006) provide a complete list of all environmental variables sampled and used in our initial analyses.

After preliminary analysis with each environmental data set it became apparent that even with strong data transformations such as log(X + 1), each data set still contained extreme values that dominated and skewed the distributions and results. Subsequently, all analyses used rank transformations to eliminate the influence of these extreme values. The multivariate BIO-ENV (biology-environment relationship using the BEST statistics routine in PRIMER) procedure in PRIMER, version 6 (Clarke and Ainsworth, 1993; Clarke and Gorley, 2006) was used to identify a subset of 5 to 10 variables in each data set that best explained the measured variation among the 28 sites from the initial larger number of variables in that data set. This procedure was completed separately for each data set, and then the final or "best of the explanatory environmental variables" were merged. The variables retained for each data set and detailed descriptions are listed in tables A3 to A8.

In addition, a nutrient index was created by taking the first principle component (first axis) of a principle component analysis (PCA) on just the variables TN and TP, then converting the resulting axis scores to a scale from 0 to 100. The first PCA axis of TN and TP explains the largest amount of variation across the 28 sites and therefore so does the nutrient index.

The algal data was analyzed using multivariate statistics and algal water-chemistry metrics were calculated using Algal Data Analysis System (ADAS) software (Tom Cuffney, U.S. Geological Survey, written commun., 2007) that interfaced with an autecological compilation of water-quality indicator traits for more than 6,000 algal taxa (Porter, 2008). ADAS also created the diatom-only taxa-by-site data matrix used for the PRIMER analyses. Nearly all sites contained a high percentage of relatively small nondiatom taxa (mostly blue-green and red algae) that overshadowed the signal from the diatoms. Much information is available on the tolerances and preferences of diatoms for several water chemistry parameters including nutrients, specific conductance, dissolved oxygen (DO), pH, temperature, amount of organic matter, and current velocity. Therefore, multivariate and algal metric analyses were performed only on diatom data, and all-taxa datasets were characterized by relative density (number of cells/cm^2).

The Invertebrate Data Analysis System software (IDAS; Cuffney, 2003) was used to resolve taxa ambiguities for invertebrate data and to calculate about 140 benthic macroinvertebrate metrics commonly used in bioassessment (Davis and Simon, 1995; Barbour and others, 1999). Cuffney (2003) and Cuffney and others (2005) describe and discuss the issues of benthic macroinvertebrate taxa ambiguities that are beyond the scope of this report. The benthic macroinvertebrate metrics included measures of richness, percentage richness, density, percentage density, dominance, organism tolerance, and assemblage diversity. The tolerance metrics reported were based on the combination of regional tolerance values for the Pacific Northwest (B. Wisseman, Aquatic Biology Associates, Inc., written commun., 2003) or on professional judgment for taxa not covered in the Wisseman regional list. All tolerance values assigned to taxa followed the standard U.S. Environmental Protection Agency (USEPA) tolerance scoring of 0 to 10 from least to most tolerant (Barbour and others, 1999, Cuffney, 2003). Tolerance values then were compared to national and Pacific Northwest regional values reported by Cuffney (2003) to assure consistency and appropriateness. Tolerance metrics were calculated based on richness and abundance (Cuffney, 2003).

All invasive-fish counts were summed to create an aggregated nonnative “pseudospecies” to substitute for the individual nonnative counts (10) due to their limited individual occurrences among the sites. A fish index that summed the scores from four individual metrics also was computed: percentages of salmonids, reticulate sculpins, nonnative species and natives with reticulate and salmonids removed. Site values were given scores of 8, 4, 2, or 1 if the value fell within different quartiles (less than 25 percent, 26 to 50 percent, 51 to 75 percent, or greater than 75 percent). Scores from the four metrics then were summed and converted to a 0 to 100 scale “fish index,” with higher values indicating a more natural fish assemblage. The two native ammocoete lamprey (*Lampetra*) species were combined into the single category.

Biological data matrices commonly have numerous zero values and a few extreme values, resulting in a highly skewed distribution that requires some form of transformation to bring it closer to a normal distribution before statistical analyses can be completed (Legendre and Legendre, 1998; Clarke and Gorley, 2006). For all multivariate analyses, diatom density data was transformed using the square root function and benthic macroinvertebrate counts were converted to abundance values in number per square meter and log transformed (X + 1). The abundance data for fish species were log transformed (X + 1) to create the site-species matrix for multivariate analysis.

Relating Biological Assemblages to Environmental Factors

Associations between the environmental and biological data (algae, benthic macroinvertebrates, and fish assemblages) were examined using Spearman rank correlations (SAS version 8: Delwiche and Slaughter, 1998) and PRIMER multivariate statistical analyses (ordinations). Nonmetric dimensional scaling (nMDS) ordinations of the full assemblage data (for fish and benthic invertebrates) or the diatoms-only assemblage (for algae) were generated using Bray-Curtis similarity matrices for each biological assemblage (PRIMER, version 6: Clarke and Gorley, 2006). This method reduces the complex multidimensional nature of ecological data (for example, multiple species across many sites) to a reduced set of axes (1–4) that attempts to capture as much strength and explained variation among sites as the original multidimensional data matrix (for more detailed information on multivariate ordinations see Legendre and Legendre 1998). The result is a 2-axis plot where samples (sites) are positioned according to degree of similarity in taxonomic composition with each other. The goal is to reduce the complex multivariate species data to two ordination axes, which then may be correlated with environmental factors that may influence the species composition. In addition, the environmental matrix (Euclidian distance similarity) was related directly to the ecological matrices using the BEST procedure in PRIMER to determine the final subset of the environmental variables that best describe the variation in the ecological species matrix (nMDS ordination) among the 28 sites.

In this report, Spearman rank correlation coefficients (rho values) were considered strong when greater than or equal to 0.66 and moderate when between 0.66 and 0.50. All rho values greater than 0.50 were statistically significant at P less than 0.05. The different analytical techniques used, such as scatter plots, summary graphs, correlations, and multivariate analyses, although common and robust, do not prove direct cause and effect. They are useful, however, for providing insights into ecological processes, for revealing potential environmental pathways, and for generating hypotheses.

Results

Physical Characteristics

Geographic Setting

Urban and agricultural watershed development in the Willamette River basin and surrounding area followed the prevailing natural regional topography: most development was in the flat valley lowlands rather than in the higher elevation foothills and mountains. This was evident by the strong correlation between the natural environmental setting metrics (mean and minimum watershed elevation) and the urban indicator metrics (UII, percentage impervious surface, POPDEN00, percentage urban + agriculture, and ROADDEN (table 2). Environmental setting affected the natural characteristics of streams through variations in precipitation, erosion, and instream habitat as mediated by natural channel geomorphology and geology. Therefore, even without human influence, there were minor to moderate differences from the higher gradient foothill streams to the low-gradient valley streams. However, many of the environmental setting metrics overemphasized these differences because some variables were calculated for the whole watershed and not just the local area surrounding the sampling site. A good example was mean watershed slope and watershed elevation. Because many streams in the Willamette River basin and surrounding area originated in the foothills or mountains, calculated watershed metrics included parts of the higher elevation and higher gradient reaches even though the characteristics of the stream at the sampling site reflected the location of the stream with a low-gradient valley. The environmental setting metrics were calculated this way to provide measures of watershed characteristics that were consistent nationally and simple to calculate. There was an effort to minimize the natural differences among sites by selecting stream sampling reaches that were within the low-gradient valley, even though a large part of the upper watershed may be in a different ecoregion. For example, 75 percent of the sites were within 80 m of the overall mean elevation of 220 m; sites ranged between 50 m and 620 m in elevation. Correlation of minimum watershed elevation to the urban indicator metrics, although still moderately statistically significant, was somewhat lower than the correlation of mean watershed elevation to the urban indicator metrics (table 2).

Stream Hydrology

Increased flow variability, or stream "flashiness" in the form of frequent high peaks and low troughs, is considered a key effect of urbanization on streams (Paul and Meyer, 2001; McMahon and others, 2003; Konrad and Booth, 2005; Roy and others, 2005). Konrad and Booth (2005), after reviewing the literature and analyzing a small number of sites with streamflow gaging stations from reference and urban dominated land use watersheds, determined that the frequency of "high-flow events as measured as the number of events three times above the median flow" and the "percent daily change" (flashiness) were the two most sensitive measures of changes in hydrographs due to urbanization. In their analysis, these two variables also were significantly correlated with algae, macroinvertebrates, and fish assemblage metrics. Data from this EUSE study corroborates these findings. For example, the four hydrologic variability metrics PeriodF5, PeriodF9, PeriodR5, and Richards-Baker Flashiness Index (Rb-flash), which related to rate in streamflow change, had

Table 2. Correlations of urban indicator metrics and environmental setting metrics, Willamette River basin and surrounding area, Oregon and Washington.

[See appendix A for variable definitions. Correlation coefficients were considered strong when ≥ 0.66 (bolded and shaded) and moderate when 0.66 > *rho* ≥ 0.5 (bolded). **Abbreviations:** ROADDEN, road density; m, meter. **Symbols:** ≥, greater than or equal to; >, greater than; –, not applicable]

Urban indicators	Mean soil erodibility	Watershed elevation		Organic matter (mean percent)	Annual precipitation	Water surface slope (mean percent)	Water depth (mean depth)
		Mean	Minimum				
Urban indicator metrics							
Urban intensity index (UII)	**0.63**	**-0.87**	**-0.53**	**-0.61**	**-0.71**	**-0.81**	**-0.70**
Percent impervious surface	**.57**	**-.90**	**-.59**	**-.64**	**-.67**	**-.85**	**-.68**
POPDEN00	**.60**	**-.88**	**-.55**	**-.62**	**-.70**	**-.81**	**-.69**
Percent urban + agriculture	**.55**	**-.87**	**-.52**	**-.53**	**-.62**	**-.90**	**-.53**
ROADDEN	**.52**	**-.81**	-.48	**-.54**	**-.66**	**-.76**	**-.65**
Environmental setting metrics							
Mean watershed elevation (m)	**-0.75**	–	**0.76**	**0.72**	**0.76**	**0.81**	**0.70**
Minimum watershed elevation (m)	**-.71**	**0.76**	–	**.59**	**.63**	.40	**.68**

significant correlation with the urban indicator metrics (table 3). PeriodF5, PeriodF9 and PeriodR5 were metrics that summarized the frequency of periods of falling (F) or rising (R) stream-discharge events, where hourly stream-discharge change was greater than or equal to 5 or greater than or equal to 9 multiplied by the median decrease or increase over the period of record (table A5). For example, PeriodF5 referred to the number of hours when streamflow fell over the period of record by at least five times the median flow for that site. The Rb-flash characterizes the degree that streamflow changed relative to the daily median. PeriodF9, the metric that documented the number of falling hydrologic events greater than nine times the site median, had the strongest correlation values—rho 0.69 with the UII (fig. 5) and 0.71 with road density (ROADDEN) (table 3). Associations among pairs of variables are shown as regression graphs (figs. 5 and 6) with simple linear or curvilinear trend lines added to aid interpretation.

Table 3. Spearman's rank correlations between urban indicator and water-chemistry metrics and select environmental variables, Willamette River basin and surrounding area, Oregon and Washington.

[See appendix A for variable definitions. Correlation coefficients were considered strong when absolute value ≥ (bolded and shaded) and moderate when 0.66 > *rho* ≥ 0.5 (bolded). **Abbreviations:** ROADDEN, road density; TEQ, toxic equivalents; SPMD, semipermeable membrane device. **Symbols:** ≥, greater than or equal to; >, greater than]

Stream and reach-scale variables	Urban indicators				
	Urban intensity index (UII)	Impervious area (percent)	POPDEN00	Urban + agriculture (percent)	ROADDEN
Hydrologic variation metrics					
Number of falling events > 5×median (PeriodF5)	**0.69**	**0.64**	**0.68**	**0.52**	**0.70**
Number of falling events > 9×median (PeriodF9)	**.69**	**.65**	**.67**	**.51**	**.71**
Number of rising events > 5×median (PeriodR5)	**.65**	**.62**	**.65**	.48	**.68**
Richards-Baker Flashiness Index (Rb-flash)	**.56**	.49	**.55**	.41	**.53**
Water temperature metrics					
Minimum temperature (95th percentile)	**0.56**	**0.51**	**0.56**	0.44	**0.53**
Habitat metrics					
Mean embeddedness (riffle and runs)	**0.59**	**0.58**	**0.57**	**0.57**	0.49
Mean width/depth ration (riffle and runs)	**-.51**	**-.51**	**-.52**	-.47	-.49
Percent riffle habitat	**-.63**	**-.61**	**-.63**	**-.57**	**-.55**
Percent large substrate	-.30	-.23	-.30	-.24	-.27
Mean habitat heterogeneity	.30	.21	.29	.20	.28

Stream and reach-scale variables	Water-chemistry variables							
	Summer-time dissolved oxygen	Dissolved organic carbon	Total insecti-cides	Total pesticides	TEQ (SPMD)	Average specific conduc-tance	Sulfate concen-tration	Total nitrogen concen-tration
Hydrologic variation metrics								
Number of falling events > 5×median (PeriodF5)	-0.45	**0.71**	**0.71**	**0.50**	**0.70**	0.42	**0.56**	0.40
Number of falling events > 9×median (PeriodF9)	-.40	**.62**	**.68**	.48	**.67**	.49	**.66**	.43
Number of rising events > 5×median (PeriodR5)	-.37	**.60**	**.65**	.45	**.68**	.34	**.52**	.40
Richards-Baker Flashiness Index (Rb-flash)	-.40	**.70**	**.62**	.46	**.63**	.39	**.53**	.30
Water temperature metrics								
Minimum temperature (95th percentile)	**-0.53**	**0.67**	0.57	0.42	0.45	0.28	0.32	0.22
Habitat metrics								
Mean embeddedness (riffle and runs)	**-0.66**	0.46	0.36	0.39	0.41	**0.69**	**0.55**	**0.52**
Mean width/depth ration (riffle and runs)	**.50**	-.34	-.26	-.10	-.24	**-.59**	**-.50**	-.35
Percent riffle habitat	**.84**	**-.60**	-.39	-.33	-.49	**-.61**	**-.57**	-.46
Percent large substrate	.48	-.21	-.12	-.06	-.00	-.36	-.14	-.05
Mean habitat heterogeneity	**-.61**	.38	.29	.25	.18	.31	.14	-.05

Water Temperature

Water temperature metrics generally did not correlate strongly with any urban indicator metrics; however, the minimum water temperature metric (95th percentile) was positively correlated with the UII (0.56) (table 3) and negatively correlated with pollution sensitive diatoms (presented in the algae section, below). Because site selection was restricted to valley streams, the natural range in water temperature was narrow compared with the range in larger geographic areas or other ecosystems. Temperature data were lost during the hot summer months at three sites (Silk, Chehalem, and South Scappoose Creeks) due to transducer failure.

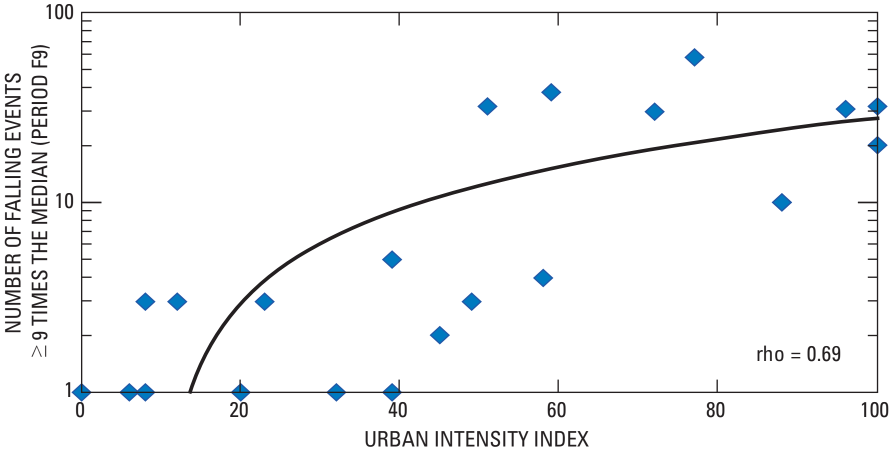


Figure 5. Relation between urban intensity index (UII) and number of falling hydrologic events greater than or equal to 9 times the median, Willamette River basin and surrounding area, Oregon and Washington.

Stream Habitat

Stream habitat metrics did not have particularly strong correlation values with any urban indicator metrics; the strongest correlation was between percentage of riffle habitat and UII and POPDEN00, rho = -0.63 (table 3). The weak correlations among habitat metrics and urban indicator metrics likely were due to the study design; sites were selected to minimize natural differences to increase the chances of isolating the effects of urbanization (Short and others, 2005). Therefore, habitat measurements may have a better relation to changes in urbanization than was revealed in this study. Although not strongly correlated to urban indicators, certain habitat metrics did correspond well to water-chemistry metrics. For example, percentage of riffle habitat was strongly correlated with the summer DO concentrations (rho = 0.84; fig. 6).

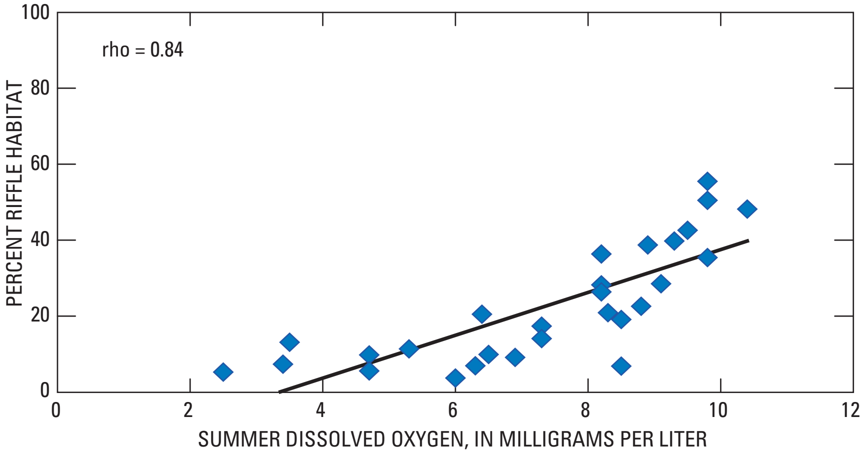


Figure 6. Percentage of riffle habitat in relation to summer dissolved oxygen concentrations, Willamette River basin and surrounding area, Oregon and Washington.

Chemical Characteristics

Pesticide Occurrence

Ninety-six stream samples were analyzed for 64 pesticides and degradation compounds. Among the samples, 28 pesticides or degradates were detected including 12 herbicides, 8 insecticides, 2 fungicides, and 6 degradates (fig. 7). At least one pesticide or degradation product was detected in 83 percent of the samples. Among all samples, the six most frequently detected pesticides were herbicides and herbicide degradates: atrazine, deethylatrazine (degradate of atrazine), simazine, hexazinone, prometon, and metolachlor. The highest frequency of occurrence was for atrazine, detected in 49 percent of all samples. Other pesticides with at least 10 detections include 3,4-dichloroaniline (degradate of diuron, and other phenylurea herbicides), tebuthiuron, trifluralin, carbaryl, diazinon, chlorpyrifos, metalaxyl, and myclobutanil. Ten or more pesticides were detected at 7 sites in either the spring or summer sampling; North Fork Deep Creek had 10 or more detections in both samplings (table 4).

Generally, individual pesticide concentrations were relatively low (fig. 7). The median concentration for any pesticide was 0.02 µg/L or less, and only seven pesticide concentrations exceeded 0.1 µg/L. The highest concentration of any sample was 1.72 µg/L for atrazine, and the highest combined pesticide concentration for a sample was 2.08 µg/L, occurring at Battle Creek during the spring 2004 sampling.

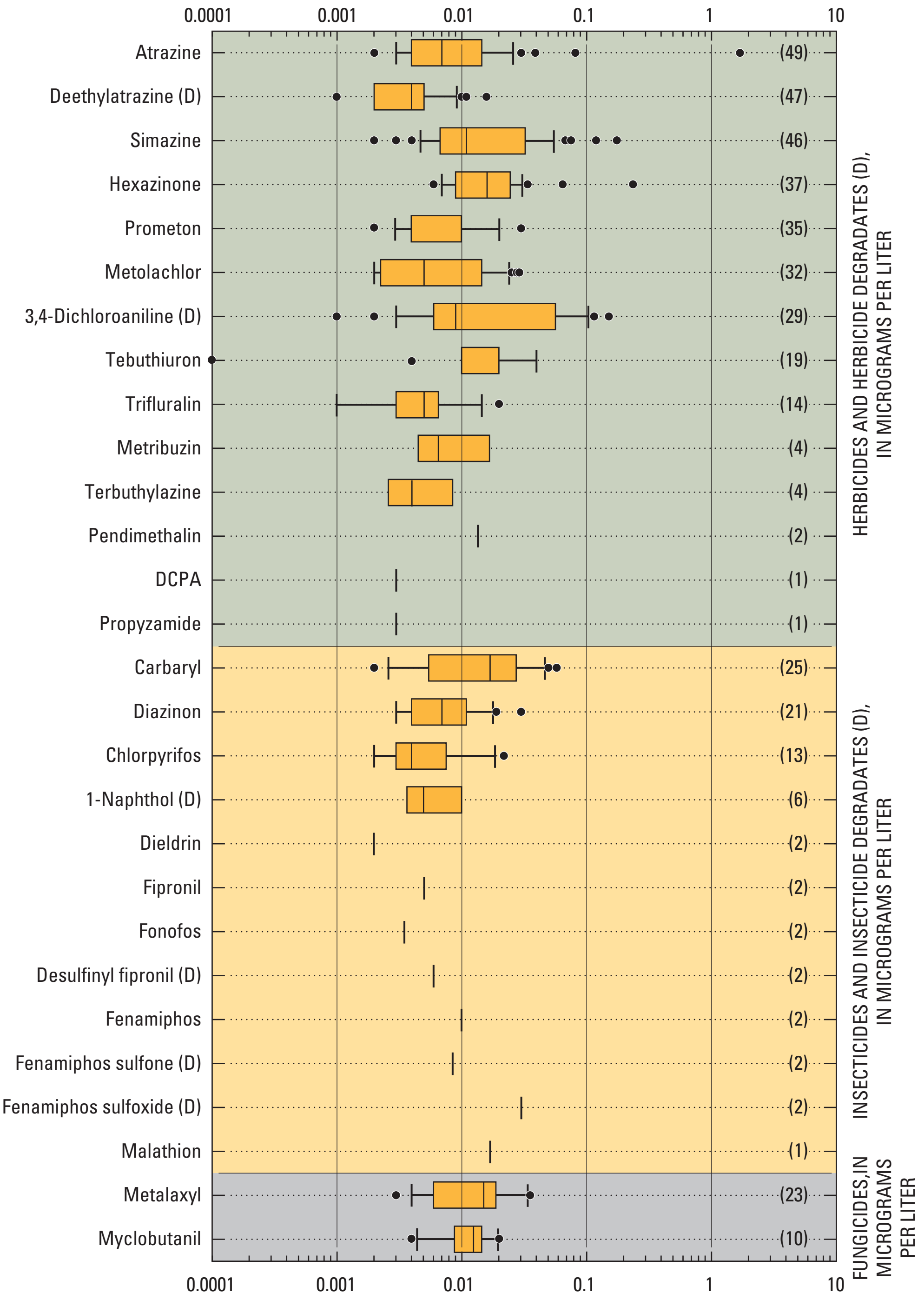


Figure 7. Pesticide concentrations and detection frequency for all stream samples, Willamette River basin and surrounding area, Oregon and Washington.Number in parentheses is equal to the total detections for that compound.

Seasonal Variability

On average, there were more pesticide detections and higher pesticide concentrations during the spring sampling than during the summer (tables 4 and 5). For example, nearly twice as many pesticides were detected in spring, including 116 herbicides (including 24 degradates), 27 insecticides (including 4 degradates) and 8 fungicides, compared to summer when 61 herbicides (including 16 degradates), 16 insecticides (including 2 degradates) and 7 fungicides were detected (table 4). During spring sampling, 5 or more pesticides were detected at 16 sites, whereas during summer, at least 5 pesticides were detected at only 7 sites. Salmon Creek and Iler Creek, two minimally effected sites, were the only two streams with no pesticide detections in either spring or summer samplings. Most pesticide detections were in North Fork Deep Creek in both sampling periods likely because this area includes the highest amount of agricultural land use (48 percent) of any of the watersheds (U.S. Geological Survey, 2005). In addition to higher frequency of detections in the spring, total pesticide concentration for spring was more than 3 times greater than in summer, although a large part of this difference was due to one large concentration at Battle Creek, Oregon, during the spring sampling (table 5).

Herbicides were detected at 25 sites during the spring sampling and 19 sites in the summer (table 4). Atrazine, hexazinone, deethylatrazine, simazine, and prometon were the five most commonly detected herbicides in the spring, all with a detection frequency greater than 46 percent. During summer sampling the highest detection frequencies were for deethylatrazine, simazine, prometon, 3,4-dichloroaniline, and metolachlor, ranging between 25 and 43 percent, with prometon being the highest. Unlike atrazine, which primarily is used for agricultural purposes, and simazine, which is used in both urban and agricultural applications, prometon is used mostly for nonagricultural purposes, such as domestic and commercial applications to driveways, fence lines, lawns, and gardens. Prometon also can be used as an asphalt additive (Gilliom and others, 2006). Previous research documented a direct relation between urban land use and prometon detection frequency in surface water and ground water (Koplin and others, 1998), so it was not surprising to see such a high frequency of detection in our study. Where insecticides were detected, carbaryl and diazinon were predominant. Carbaryl, an agricultural and urban insecticide, was detected 39 percent of the time in spring and 18 percent in summer. Diazinon was detected slightly less than carbaryl in spring at 29 percent, yet slightly more in summer at 21 percent. Due to changes in pesticide regulations, residential uses of diazinon were cancelled in 2004, but use is still approved for agriculture.

Temporal Variability

During the 10 site “high frequency” sampling effort, pesticides were detected in all samples (6 sample times) for the 3 most highly-urbanized sites (Claggett, Pringle, and Kellogg Creeks) and in 2 mixed agricultural-urban sites (North Fork Deep and Tickle Creeks) (table 4). Pesticides were detected most frequently at North Fork Deep Creek, with at least eight pesticides detected in each sample. The fewest pesticides were detected in Salmon Creek, a predominantly forested watershed (UII = 20), with only one detection in March 2004. This relatively low pesticide detection frequency in Salmon Creek likely was due to the low amount of agricultural land in this watershed (2 percent). Three pesticides were detected in three of the six samplings (50 percent) in the East Fork Dairy Creek watershed, even though it had only 1 percent combined urban plus agriculture land use (the site with the UII = 0). This probably was due to the close upstream proximity to the sampling site of a variety of agricultural activities (for example, Christmas tree plantations and nursery operations) even though they were of small acreage and therefore did not add significantly to the total of agricultural land use summarized as a percentage of the total watershed area.

Overall, 44 of the 60 samples collected contained 2 or more pesticides and 11 of the 60 samples contained 10 or more pesticides. On average, between 5 and 11 pesticides were detected at the 3 most highly-urban sites during the 6 high frequency samplings, and between 1 to 3 pesticides were detected at the 3 lowest-urban sites. Streams draining predominantly urban watersheds have been shown to have higher detection frequencies and concentrations of some insecticides than other types of land uses (Anderson and others, 1997; Gilliom and others, 2006), and the results for this study followed this pattern. High frequency samples collected at the 3 most urban sites (UII ≥ 88) (table 1) had a detection of at least one insecticide in 58 percent of samples; whereas high frequency samples collected at the 3 least urban sites (UII ≤ 20) had insecticide detections in only 8 percent of samples.

Pesticide Metrics in Relation to Urban Intensity Index

Relations between the UII and pesticide occurrence were strongest when considering the total number of pesticides and total concentration of all pesticides in a sample. For the spring and summer samplings a high UII was associated with a large number of pesticides detected in a sample. Comparison among groupings of sites based on the four levels of UII shaded in tables 4 and 5 (low: less than 10; medium: 10 to 25; high: 25 to 70; and very high: greater than 70) reveals some

Table 4. Number of pesticide detections at each site by pesticide type for spring and summer 2004, Willamette River basin and surrounding area, Oregon and Washington.

[Sites are sorted by urban intensity index (UII). Shading from light to dark represents low, medium, high, and very high UII scores. **Abbreviations:** OR, Oregon; WA, Washington. **Symbols:** ≥, greater than or equal to; >, greater than; <, less than; ≤, less than or equal to]

Site name	UII	Spring sampling				Summer sampling				Total detections
		Herbicide	Insecticide	Fungicide	Total	Herbicide	Insecticide	Fungicide	Total	
Beaverton Creek near SW 216th Avenue, near Orenco, OR	100	7	2	1	10	3	0	1	4	14
Claggett Creek at Keizer, OR	100	7	1	0	8	4	2	0	6	14
Fanno Creek at Durham, OR	96	8	2	0	10	1	2	1	4	14
Pringle Creek at Salem, OR	88	7	1	0	8	3	0	0	3	11
Kellogg Creek at Milwaukie, OR	88	7	0	0	7	6	1	0	7	14
Amazon Creek near Danebo Road, at Eugene, OR	77	2	2	0	4	0	3	0	3	7
Tryon Creek below Nettle Creek, near Lake Oswego, OR	72	2	3	0	5	5	3	0	8	13
Curtin Creek near Vancouver, WA	69	5	0	1	6	2	0	0	2	8
Johnson Creek at Circle Avenue, OR	59	8	1	1	10	4	1	1	6	16
Battle Creek near Turner, OR	58	8	2	0	10	6	0	0	6	16
Rock Creek at Quatama Road, near Hillsboro, OR	51	8	2	0	10	3	0	0	3	13
Whipple Creek near Salmon Creek, WA	49	2	1	0	3	0	0	0	0	3
Chicken Creek near Sherwood, OR	45	6	2	0	8	1	0	0	1	9
North Fork Deep Creek at Barton, OR	39	8	2	2	12	7	1	2	10	22
Oak Creek at Corvallis, OR	39	1	0	0	1	0	0	0	0	1
Tickle Creek near Boring, OR	32	6	1	1	8	7	2	1	10	18
Chehalem Creek at Newberg, OR	29	7	2	0	9	2	1	0	3	12
Silk Creek near Cottage Grove, OR	24	1	0	0	1	2	0	0	2	3
Rock Creek near Battleground, WA	23	1	3	1	5	0	0	1	1	6
Salmon Creek near Battleground, WA	20	0	0	0	0	0	0	0	0	0
Deep Creek near Sandy, OR	17	4	0	1	5	2	0	0	2	7
Nate Creek near Colton, OR	15	4	0	0	4	1	0	0	1	5
Milk Creek at Camp Adams, OR	12	2	0	0	2	1	0	0	1	3
South Scappose Creek at Scappose, OR	8	1	0	0	1	0	0	0	0	1
North Yamhill Creek near Yamhill, OR	8	0	0	0	0	1	0	0	1	1
Lost Creek near Dexter, OR	6	1	0	0	1	0	0	0	0	1
Iler Creek near Forest Grove, OR	4	0	0	0	0	0	0	0	0	0
East Fork Dairy Creek near Meacham Corner, OR	0	3	0	0	3	0	0	0	0	3
Total		116	27	8	151	61	16	7	84	235
Urban intensity index						**Averages**				
UII ≥ 70	89	5.7	1.6	0.1	7.4	3.1	1.6	0.3	5.0	12
UII >25 – <70	47	5.9	1.3	.5	7.7	3.2	.5	.4	4.1	12
UII >10 – ≤ 25	19	2.0	.5	.3	2.8	1.0	0	.2	1.2	4
UII ≤ 10	5	1.0	0	0	1.0	.2	0	0	.2	1

Table 5. Summary statistics of pesticide concentrations collected during spring and summer 2004, Willamette River basin and surrounding area, Oregon and Washington.

[Pesticide concentrations are in micrograms per liter. Sites are sorted by urban intensity index (UII). Shading from light to dark represents low, medium, high, and very high UII scores. **Abbreviations:** OR, Oregon; WA, Washington; SW, southwest. **Symbols:** ≥, greater than or equal to; >, greater than; <, less than; ≤, less than or equal to]

Site name	UII	Sum pesticide		Sum pesticides (spring and summer)		
		Spring	Summer	Insecticide	Herbicide	Fungicide
Beaverton Creek near SW 216th Avenue near Orenco, OR	100	0.077	0.053	0.012	0.090	0.028
Claggett Creek at Keizer, OR	100	.100	.105	.042	.167	0
Fanno Creek at Durham, OR	96	.132	.055	.079	.094	.014
Pringle Creek at Salem, OR	88	.050	.037	.003	.084	0
Kellogg Creek at Milwaukie, OR	88	.064	.065	.006	.123	0
Amazon Creek near Danebo Road at Eugene, OR	77	.068	.062	.096	.034	0
Tryon Creek below Nettle Creek, near Lake Oswego, OR	72	.025	.066	.037	.054	0
Curtin Creek near Vancouver, WA	69	.026	.007	0	.029	.004
Johnson Creek at Circle Avenue, OR	59	.361	.225	.022	.498	.066
Battle Creek near Turner, OR	58	2.08	.158	.026	2.21	0
Rock Creek at Quatama Road near Hillsboro, OR	51	.214	.055	.054	.220	0
Whipple Creek near Salmon Creek, WA	49	.014	0	.002	.012	0
Chicken Creek near Sherwood, OR	45	.083	.035	.016	.102	0
North Fork Deep Creek at Barton, OR	39	.259	.161	.019	.354	.047
Oak Creek at Corvallis, OR	39	.008	0	0	.008	0
Tickle Creek near Boring, OR	32	.049	.058	.011	.071	.025
Chehalem Creek at Newberg, OR	29	.190	.057	.019	.232	0
Silk Creek near Cottage Grove, OR	24	.018	.038	0	.056	0
Rock Creek near Battleground, WA	23	.060	.015	.038	.002	.035
Salmon Creek near Battleground, WA	20	0	0	0	0	0
Deep Creek near Sandy, OR	17	.039	.018	0	.054	.003
Nate Creek near Colton, OR	15	.023	.002	0	.025	0
Milk Creek at Camp Adams, OR	12	.018	.005	0	.023	0
South Scappose Creek at Scappose, OR	8	.004	0	0	.004	0
North Yamhill Creek near Yamhill, OR	8	0	.010	0	.010	0
Lost Creek near Dexter, OR	6	.007	0	0	.007	0
Iler Creek near Forest Grove, OR	4	0	0	0	0	0
East Fork Dairy Creek near Meacham Corner, OR	0	.013	0	0	.013	0
Total		3.99	1.29			
Urban intensity index		**Averages**				
UII ≥ 70	89	0.074	0.063	0.039	0.092	0.006
UII > 25 – < 70	47	.329	.076	.017	.374	.014
UII > 10 – ≤ 25	19	.026	.013	.006	.027	.006
UII ≤ 10	5	.005	.002	0	.007	0

interesting patterns. For example, when summed across the spring and summer samplings, an average of 12 pesticides were detected in both the high and very high UII groups (table 4). The number of detections dropped substantially, four pesticides detected on average, when only looking at medium UII sites and only one pesticide was detected on average in low UII sites (UII less than 10) (table 4). The pattern of herbicide concentrations varied from this, as average total herbicide concentrations were higher for high UII sites than when compared to very high UII sites (UII greater than 70), even though the number of herbicide detections were the same between these two groups of sites. The higher herbicide concentrations of the high UII group compared to the very high UII group remained even after the extreme herbicide value from Battle Creek was removed. However, for insecticides, the average concentration was more than 2.5 times greater in the very high UII group of sites than the high UII group.

The fact that the high UII group averaged as many pesticide detections as the very high group, likely was due to the influence of agricultural land use in the watersheds. The amount of agricultural land in the watersheds in the high UII group ranged from 16 to 48 percent (an average of 31 percent), and the amount of urban ranged 7 to 72 percent (an average of 30 percent) (table 1; fig. 8). Therefore, many high category UII watersheds had about the same amount of influence from agricultural land use as urban land use. On the other hand, the very high UII category, which was dominated by urban land use (60–98 percent urban), had a relatively minor influence from agricultural land use (0–8 percent agriculture). In terms of the number of pesticides detected in streams, little difference was observed between agricultural and urban land; however, the composition of the pesticide mixture and the timing of delivery to the stream varied considerably between agricultural and urban sites in the study. These differences in pesticide detection frequency and types of pesticides between agriculture and urban land use are similar to those reported in the Willamette Valley by Anderson and others (1997) and in streams across the country by Gilliom and others (2006).

Among individual pesticides detected during this study, only prometon showed a significant correlation with UII (rho = 0.70), and then only during the spring sampling. Total pesticide and insecticide concentrations (log transformed due to extreme values that skew the distribution; log [X + 0.0001] summed across spring and summer) were strongly correlated with the UII (rho = 0.68 and 0.69, respectively) (figs. 9, 10, and table 6). The correlation of log total pesticide concentration increased slightly when correlated to percentage urban plus agricultural land (rho = 0.72), yet the correlation decreased dramatically when related to only percent agricultural land (rho = 0.41). Conversely, the correlation of log total insecticide concentration decreased when related to urban plus agricultural land compared to its correlation to UII (rho = 0.63 and 0.69, respectively) (table 6). This suggests that many insecticide detections originated from applications in urban areas, not from the agricultural uses.

Pesticide Toxicity Index in Relation to Urban Intensity Index

PTI scores at the 28 sites typically were greater in spring than summer (18 greater, 8 less, 2 the same). The difference between most pairs of PTI scores was small, as 20 of the 28 scores changed by one order of magnitude or less between the two samplings. The sum of the spring and summer PTI values was used to estimate the potential pesticide toxicity among sites and to follow our summary of actual pesticide detections and concentrations presented previously in this report. The sum of the PTI was significantly correlated with the UII (rho = 0.63, fig. 11*A*), yet had a stronger correlation to ROADDEN at rho = 0.69 (fig. 11*B*). The relation of PTI to ROADDEN was curvilinear and revealed two basic groups of sites with relatively high PTI values. One group of sites with the highest road density (ROADDEN greater than 10) also had the highest percentage of urban land use or highest UII values. Another group of sites with moderate road density had a combination of moderate percentage of urban land and substantial amounts of agricultural land (ROADDEN of 3.5 to 8.5 and PTI values greater than 4). This pattern followed the results of a number of pesticide detections stated above, such that high detection frequencies occurred at sites with high urban land use and at sites with lower amounts of urban land use but with moderate amounts of agricultural land.

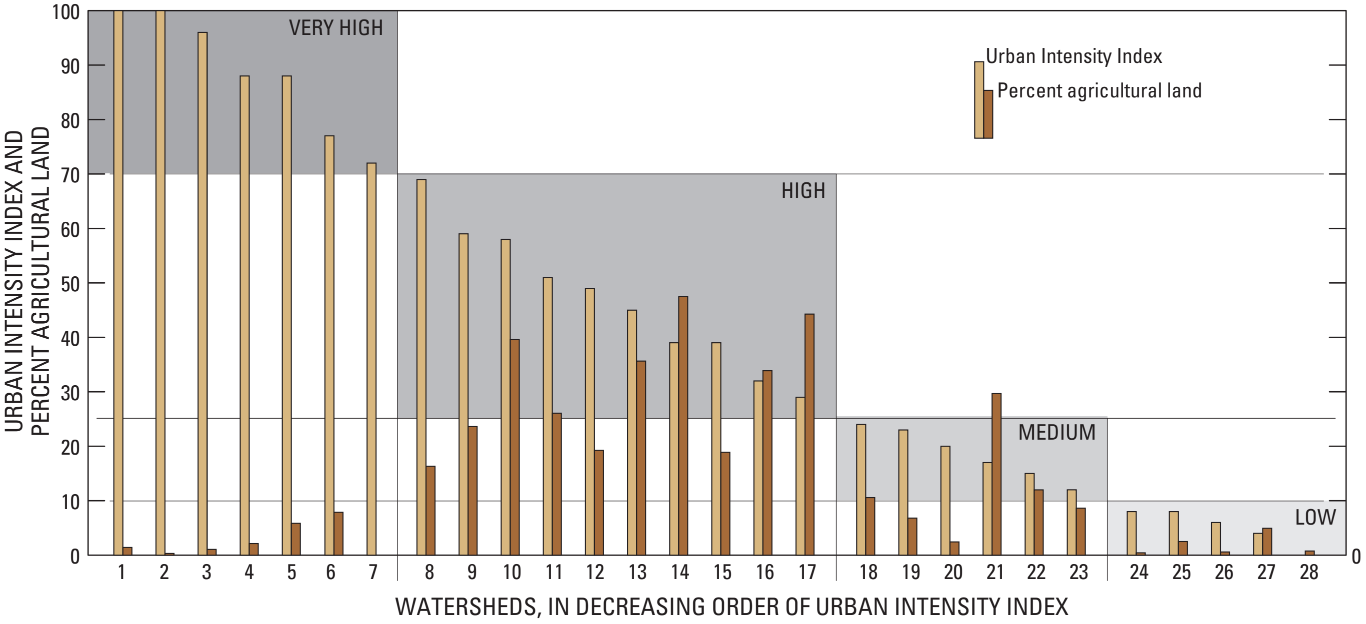


Figure 8. Urban intensity index (UII) and percentage of agricultural land for all 28 sites, Willamette River basin and surrounding area, Oregon and Washington.

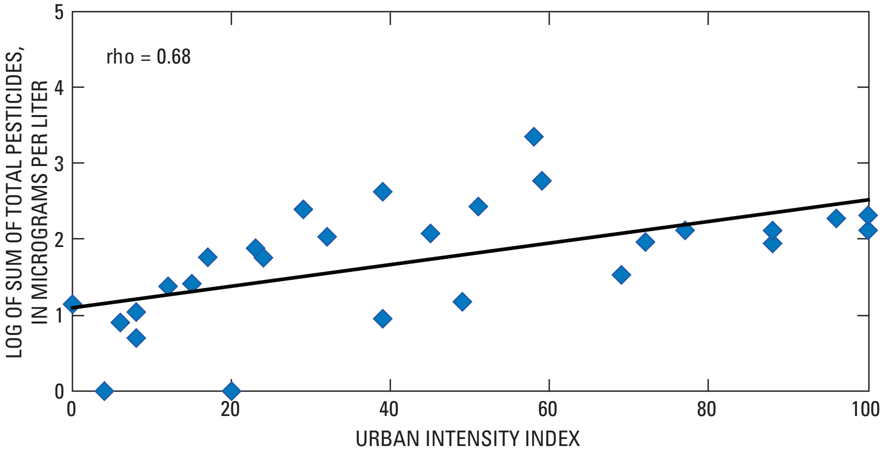


Figure 9. Total pesticide concentration in relation to urban intensity index (UII) for all 28 sites, Willamette River basin and surrounding area, Oregon and Washington.

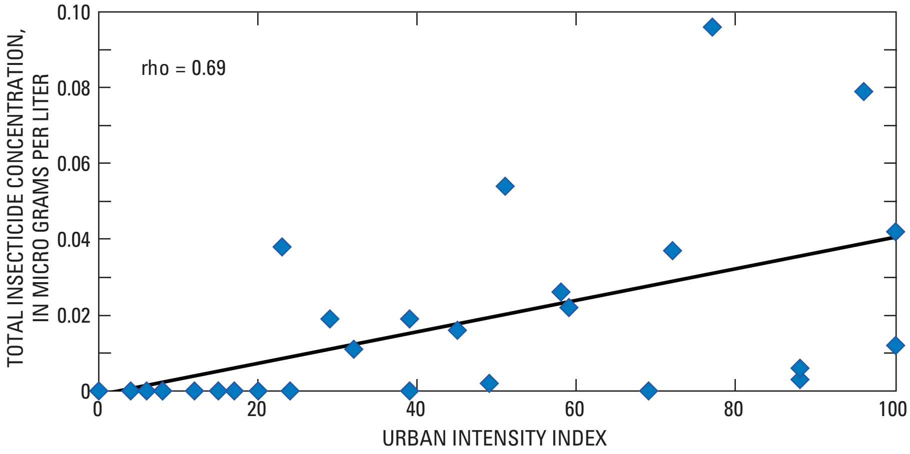


Figure 10. Total insecticide concentration in relation to urban intensity index (UII) for all 28 sites, Willamette River basin and surrounding area, Oregon and Washington.

Table 6. Spearman's rank correlation coefficients (rho values) between urban indicator and water-chemistry variables, Willamette River basin and surrounding area, Oregon and Washington.

[Average dissolved organic carbon (DOC), sulfate (SO_4), total nitrogen (TN), total phosphorus (TP) concentration values were used for the correlations. Correlation coefficients were considered strong when absolute value ≥ 0.66 (bolded and shaded) and moderate when 0.66 > rho ≥ 0.50 (bolded). **Abbreviations:** PTI, Pesticide Toxicity Index; TEQ, toxic equivalents index; DO, dissolved oxygen; ROADDEN, road density. **Symbol:** ≥, greater than or equal to]

Urban indicators	Sum of spring + summer		Water-chemistry variables								
	Insecticide	Pesticide	PTI	TEQ	Pyrene index	Summer DO	DOC	SO_4	TN	TP	Nutrient index
Urban intensity index (UII)	**0.69**	**0.68**	**0.63**	**0.81**	**0.67**	**-0.60**	**0.72**	**0.73**	**0.79**	**0.71**	**0.85**
Percent impervious surface	**.65**	**.65**	**.61**	**.80**	**.64**	**-.56**	**.65**	**.72**	**.83**	**.71**	**.86**
POPDEN00	**.70**	**.68**	**.62**	**.81**	**.66**	**-.61**	**.70**	**.71**	**.81**	**.73**	**.85**
Percent urban + agriculture	**.63**	**.72**	**.60**	**.73**	**.58**	**-.53**	**.60**	**.62**	**.86**	**.65**	**.84**
ROADDEN	**.73**	**.67**	**.69**	**.75**	**.56**	**-.54**	**.69**	**.69**	**.75**	**.65**	**.79**

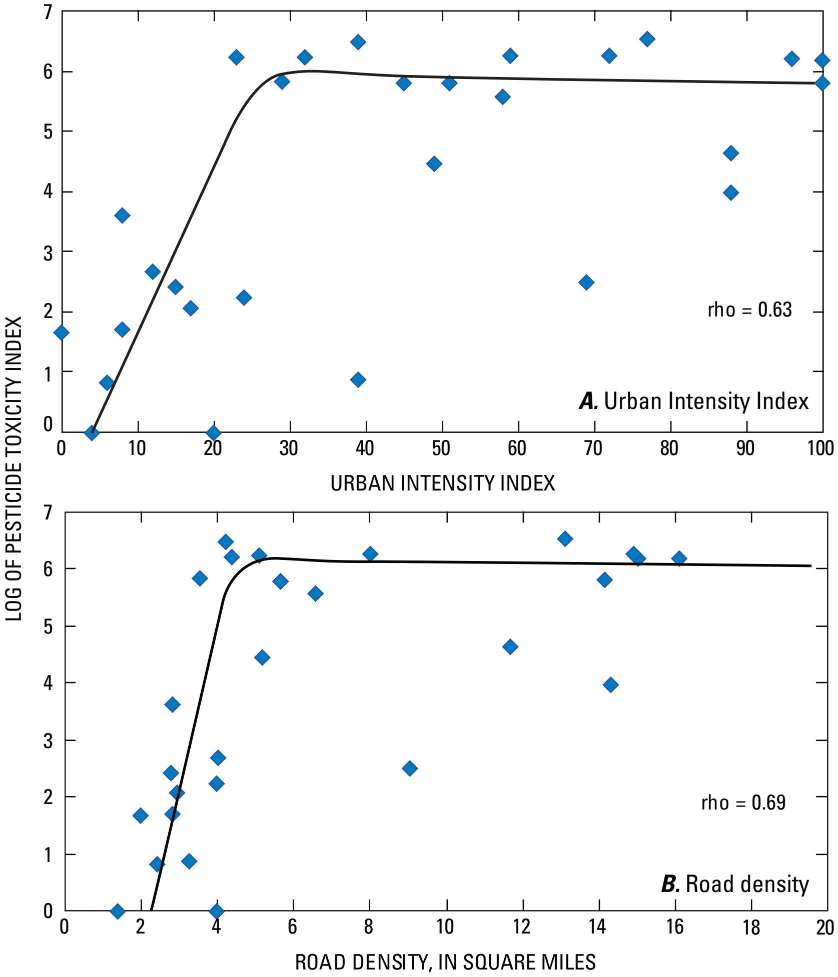


Figure 11. Relations between Pesticide Toxicity Index (PTI) and (*A*) urban intensity index (UII) and (*B*) road density (ROADDEN), Willamette River basin and surrounding area, Oregon and Washington.

Semipermeable Membrane Device Assays in Relation to Urban Intensity Index

Of the three assays run on the SPMDs, the toxic equivalents (TEQ) index (P450 RGS assay for aryl hydrocarbon receptor agonists) and Pyrene Index (fluoroscan for total PAHs) provided consistent and reliable results. No interpretable results were achieved from the Microtox® assay and are not discussed (Bryant and others, 2007). The TEQ and Pyrene Index assays were correlated to the five urban indicator metrics, with TEQ having the strongest correlation to both UII and POPDEN00 at rho = 0.81 (table 6; fig. 12). Bryant and others (2007) determined similar strong correlations of the TEQ and Pyrene indices compared to the individual UIIs of other USGS EUSE studies in Atlanta, Georgia; Raleigh-Durham, North Carolina; Denver, Colorado; Dallas-Fort Worth, Texas; and Milwaukee-Green Bay, Wisconsin. They also concluded that the strong correlation of UII with pentachloroanisole and pyrogenic PAHs in the other study areas was evidence that these compounds were an important part of urbanization regardless of geographic location.

Along with the three assays, part of each SPMD dialysate was analyzed for hydrophobic chemical compounds. Of the 141 compounds targeted for identification by gas chromatography and mass spectrometry analysis, 39 were detected in the Willamette River basin and surrounding area. In comparison, detection in the other 5 EUSE studies ranged from 49 compounds detected in Raleigh-Durham to 36 in Dallas-Fort Worth (Bryant and others, 2007). Only three PAH compounds detected in the Willamette River basin and surrounding area were significantly correlated to the UII, and this was the lowest number of significant correlations among the six EUSE studies (high of 21, Raleigh-Durham).

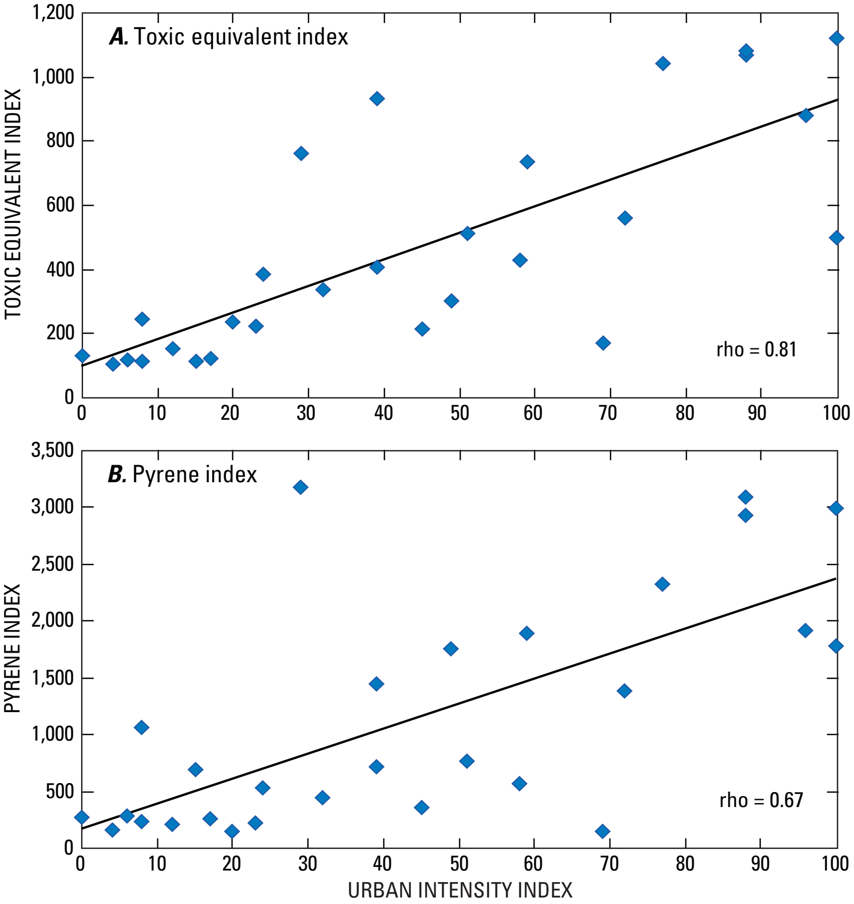


Figure 12. Relation between the urban intensity index (UII) and semipermeable membrane device results for the (*A*) toxic equivalent index (TEQ) and (*B*) pyrene index.

Nutrients and Field Parameters

For spring and summer samplings, total nitrogen (TN), total phosphorus (TP), and orthophosphorus (soluble reactive phosphorus; SRP) had positive correlations with the UII (table 6). The highest two TN concentrations of all sampling sites were in Curtin Creek during spring and summer (4.8 and 3.9 mg/L, respectively). Curtin Creek was considered an outlier due to the relatively high TN values measured, which were probably caused by the large amount of ground-water inflow (ground-water that is high in DO and TN due to the natural coarse grain geology, which likely minimizes the amount of denitrification) just upstream of the sampling site. TN concentrations averaged for the spring and summer samplings and nutrient index were positively correlated to the UII (TN: rho = 0.79; fig. 13*A*) (nutrient index: rho = 0.85; table 6). The highest TP concentration (0.18 mg/L) was in Beaverton Creek in spring, and in Claggett Creek in summer (TP = 0.28 mg/L).

Some of the highest TN values were in the medium to high UII groups of sites (UII 25 to 70), likely due to the increased amount of agricultural land at these moderately urban sites (fig. 8). As a result, the correlation of TN increased further when percentage of agricultural land was included with percentage of urban land as the correlative variable (rho = 0.86; fig. 13*B*). Nevertheless, lower TN concentrations (generally less than 0.5 mg/L) were detected in sites with relatively low urban development (UII less than 25) , whereas relatively higher TN concentrations ranging from 0.7 to 2.3 mg/L were commonly detected in higher UII sites (greater than 25), (not including the outlier value for Curtin Creek). The pattern for TP was not as consistent as shown for TN and its correlation decreased when the amount of agriculture was included (table 6), nevertheless, high UII sites generally had the highest TP concentrations ranging from 0.08 to 0.28 mg/L.

Phosphorus concentrations (TP and SRP) in many stream sites increased from spring to summer as streamflow decreased towards base-flow. This likely was due to inputs

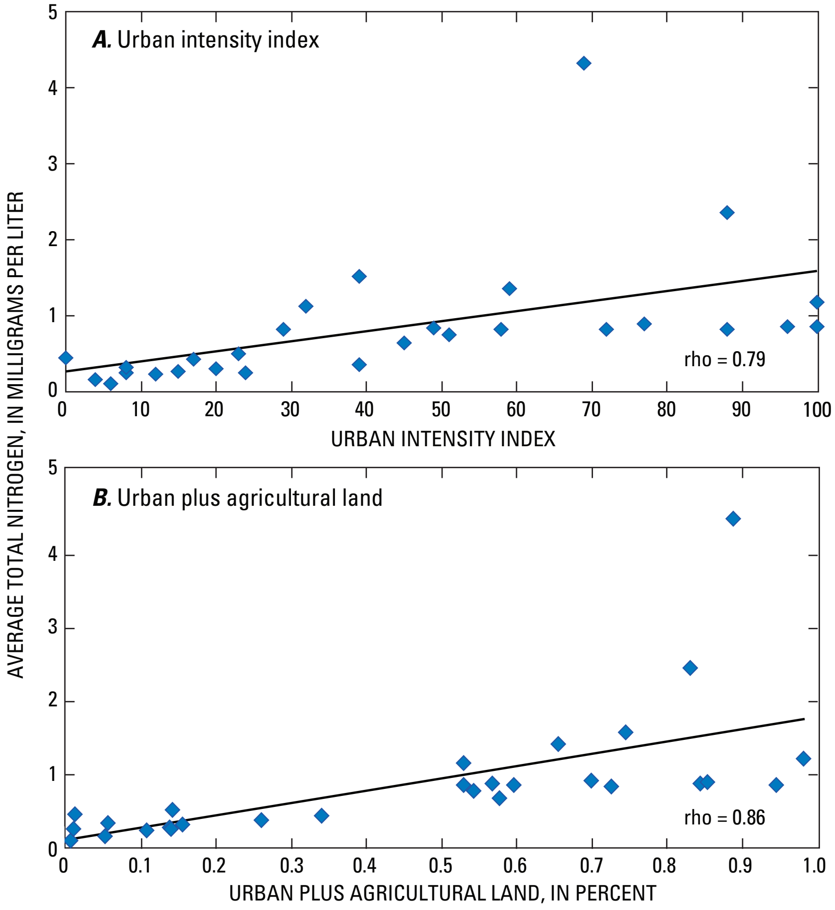


Figure 13. Relations between average total nitrogen concentrations and (*A*) urban intensity index (UII) and (*B*) percentage of urban plus agricultural land, Willamette River basin and surrounding area, Oregon and Washington.

of phosphorus in ground water to streams, though other possible explanations include increased water use and increased influences of wastewater inputs from septic systems or treatment plants. Twenty-two of the 28 sites showed this pattern of increased SRP from summer to spring. Nitrogen concentrations, however, decreased from spring to summer and were more variable than phosphorus concentrations, possibly reflecting inputs from runoff of spring fertilizer applications in urban and agricultural land that may have subsided during the dry summer months. Most streams showed decreased concentrations of dissolved inorganic nitrogen (DIN) through the growing season, which may reflect the tendency for nitrogen to be in relatively short supply compared with phosphorus in some Northwest streams, particularly during summer (Carpenter, 2003). About one-third of the streams had DIN concentrations that were 0.5 to 1.7 mg/L lower during summer compared with spring. The greatest change in the DIN concentration from spring to summer was in North Fork Deep Creek, where nuisance levels of filamentous green algae (*Cladophoraglomerata*) contributed to relatively high chlorophyll-*a* levels (157 mg/m^2).

Among the water chemistry variables, strongest correlations to the UII (rho greater than 0.70) was for DOC and dissolved sulfate (SO_4; table 6) whereas, specific conductance, bicarbonate alkalinity, chloride, and summer dissolved oxygen (DO) (negative) also were correlated, but slightly less significantly (rho greater than 0.50). Sulfate sources include fertilizers, road pavement amendments, and certain algicides (copper sulfate, for example), and is often produced during combustion. Sulfate also is produced when bacteria in organic soils oxidize hydrogen sulfide (H_2S). Potential sources of bicarbonate in urban areas include the slow erosion of concrete structures, sidewalks, and roadways, and calcium carbonate based lime products applied to lawns for pH control.

DO is a critical parameter for aquatic life in streams, and is affected by a number of processes, including water temperature, atmospheric pressure, and the activity of bacteria, algae, and other aerobic organisms that consume DO, and processes that produce it (aeration in riffles, for example, and photosynthesis by algae). All DO data used in this report were instantaneous measurements collected during midday, and do not reflect the daily cycle of DO that often occurs in nutrient-enriched streams with high algal production. It is likely that in many of these urban nutrient-enriched streams the DO may show large diurnal swings; very low DO in early morning after nighttime anerobic activity and super-saturated DO in late afternoon after photosynthesis by abundant algae.

Biological Characteristics

Algae Assemblages

Algal assemblages were dominated by pennate diatoms (Pennales Order), which comprised 214 of the 254 algal taxa identified in RTH (richest target habitat) riffle samples from the 28 sites (table 7; table A9). Based on biomass, however, Chlorphytes (green algae) were dominant, contributing on average about 70 percent of the total algal biovolume, whereas diatoms comprised 17 percent of the total algal biovolume. The most common diatoms in RTH samples were *Achnanthidium minutissimum*, *Rhoicosphenia*

Table 7. Most common algal taxa from the five major Divisions identified in Richest Targeted Habitat samples, Willamette River basin and surrounding area, Oregon and Washington.

[**Number of streams:** One Richest Targeted Habitat (RTH) algal sample was collected from each of 28 streams. **Abbreviation:** cm², square centimeter]

Class	Order	Number of taxa	Most common algal taxa		
			Scientific name	Maximum abundance (number of cells/cm²)	Number of streams (RTH)
			Diatoms (Bacillariophyta)		
Bacillariophyceae	Pennales	214	*Achnanthidium minutissimum*	$7.3E\times10^5$	27
			Rhoicosphenia abbreviata	$7.3E\times10^5$	25
			Cocconeis placentula var. euglypta	$1.6E\times10^5$	25
			Planothidium lanceolatum	$2.2E\times10^5$	22
			Navicula minima	$3.1E\times10^5$	21
			Gomphonema kobayasii	$2.5E\times10^5$	21
			Sellaphora seminulum	$1.4E\times10^5$	21
			Achnanthes subhudsonis var. kraeuselii	$1.7E\times10^6$	17
Bacillariophyceae	Centrales	14	*Melosira varians*	$2.5E\times10^5$	16
			Blue-green algae (Cyanophyta)		
Myxophyceae	Oscillatoriales	10	*Homoeothrix janthina*	$1.2E\times10^7$	21
Myxophyceae	Chroococcales	4	*Aphanocapsa sp.*	$3.8E\times10^6$	1
Myxophyceae	Nostocales	1	*Calothrix fusca*	$4.9E\times10^4$	1
			Euglenoid algae (Euglenophyta)		
Euglenophyceae	Euglenales	1	*Trachelomonas volvocina*	$5.9E\times10^3$	2
			Green algae (Chlorophyta)		
Chlorophyceae	Oedogoniales	1	*Oedogonium sp.*	$5.7E\times10^4$	6
Chlorophyceae	Cladophorales	1	*Cladophora glomerata*	$5.0E\times10^4$	2
Chlorophyceae	Chlorococcales	4	*Scenedesmus ecornis*	$3.0E\times10^4$	2
Chlorophyceae	Chaetophorales	1	*Stigeoclonium lubricum*	$2.1E\times10^5$	1
Chlorophyceae	Volvocales	1	*Pandorina morum*	$3.3E\times10^4$	1
Chlorophyceae	Zygnematales	1	*Spirogyra sp.*	$1.0E\times10^4$	1
			Red algae (Rhodophyta)		
(Undetermined)	(Undetermined)	1	Unknown Rhodophyte Florideophycidae (chantransia stage)	$2.4E\times10^6$	25
	Total number of taxa	254			

abbreviata, *Cocconeis placentula* var. *euglypta*, *Planothidium lanceolatum*, *Navicula minima*, *Gomphonema kobayasii*, *Sellaphora seminulum* and *Achnanthes subhudsonis* var. *kraeuselii* (table 7).

Based on cell density (number of cells/cm^2) blue-green and red algae were the dominant taxa at all but one site (Deep Creek), with the blue-green *Homeothrix janthina* dominating 11 sites and unidentified red algae (vegetative "chantransia" stage) six sites (table 8). The red and blue-green algae have relatively small cells, and, therefore, tended to dominate cell densities. Many dominant diatoms, particularly at sites high on the UII, were high-nutrient (eutrophic) taxa, or preferred high TN concentrations, and were tolerant of moderate levels of DO (greater than 75 percent saturation) (table 8). Although many sites lower on the UII also were dominated by eutrophic diatom taxa, several were dominated by *Achnanthes* and *Achnanthidium* species whose water-quality preferences have not yet been established.

Sixty-seven percent of the total algal biovolume (for all RTH samples combined) was comprised of filamentous green algae, including *Cladophora glomerata*, *Stigeoclonium*, *Odeogonium*, and *Spirogyra* (table 7). The occurrence of these high-biomass forming filamentous green algae was sporadic along the UII, as they were detected at few sites despite relatively high nutrient levels. In addition to requiring high nutrients, these taxa also prefer relatively high light levels, which was limited in some streams where riparian vegetation or topographic relief provided shading. High sediment concentrations in some streams also may have limited light availability. Potapova and others (2005) determined that light conditions affected algal assemblages in streams around Salt Lake City, Utah, due to riparian vegetation, stream size, and suspended sediment. Carpenter and Waite (2000) determined filamentous blue-green algae, such as *Oscillatoria*, to be common in silt-laden agricultural streams in the Willamette Valley, possibly due to their ability to move and unbury themselves after siltation events, or from an inherent ability to grow under low light conditions.

Response in Algal Biomass to Urban Intensity Index

Benthic algal biomass was highly variable along the urban gradient, with chlorophyll-*a* values ranging from 5 to 212 mg/m^2, and showed no obvious response to urbanization (fig. 14*A*). AFDM, a measure of the organic matter present, ranged from 2.4 to 70 g/m^2, and was positively correlated with the UII (rho = 0.56; fig. 14*B*) and the nutrient index (rho = 0.72; fig. 15*A*). All but one site less than 25 on the UII had an AFDM value that indicated at least a moderate degree of organic enrichment, and many sites higher on the UII (greater than 25) exceeded the criterion to be considered organically enriched (fig. 15*A*; Biggs, 1996). Twelve of 28 streams had chlorophyll-*a* concentrations exceeding 50 mg/m^2, a low-end threshold suggested to protect recreational and aesthetic qualities of streams (Biggs, 1996). The highest chlorophyll-*a* concentrations occurred in North Fork Deep and Amazon Creeks (157 and 212 mg/m^2, respectively) due to high abundances of *Cladophora glomerata*, *Oscillatoria princes*, and *Sellaphora seminulum* (fig. 14*A*). The chlorophyll-*a* concentrations in these streams also exceeded common nuisance indicator levels for benthic algae 100–150 mg/m^2 (Horner and others, 1983; Welch and others, 1988, 1989; Biggs, 1996; Dodds and others, 1997, 1998). Proliferations of algae may develop quickly during periods of stable streamflow, especially in streams receiving nutrients. Newall and Walsh (2005) found that repeated rainfall events can stimulate algal growth in streams by providing pulses of nutrients, an effect that was enhanced by the amount of impervious surface and the degree of drainage connection within the storm-water network.

Although there was considerable variation between AFDM and DOC (fig. 15*B*), the highest AFDM values occurred when the DOC exceeded about 4 mg/L, and DOC was negatively correlated with DO concentrations (fig. 15*C*). Taken together, the relations among algal biomass, DOC, and DO indicate that algal biomass may be affecting DO levels through bacterial decomposition processes involving the production of DOC. DO also is affected, however, by water temperature and the amount of riffle habitat that aerates the water (fig. 6). Because diurnal fluctuations in DO and pH can occur from algal photosynthesis, however, the one-time instantaneous midday measurements collected for this study likely do not fully reflect the processes of photosynthesis and respiration that may occur in these streams.

Elevated levels of dissolved nutrients can stimulate the growth of benthic and planktonic algae in streams. In some cases, high-biomass forming benthic algae such as filamentous Chlorophytes (green algae) may cover streams and foul substrates when high amounts of light are available for photosynthesis (Carpenter and Waite, 2000). In addition to the prolific growths of green algae described above, another high-nutrient indicator alga—*Melosira varians*—was detected at more than 50 percent of the sites (16 sites; table 7), making up about 10 percent of the total biovolume for all RTH samples. This eutrophic diatom is also a N-heterotroph because it may use organic forms of nitrogen for energy and growth. *Melosira* is considered a high quality food item for benthic macroinvertebrates because of its high nutrient and fatty acid content. This filamentous diatom has a morphology of relatively loosely connected cells that make it susceptible to removal by disturbance such as repeated scouring flows, high water velocity, or grazing by herbivorous benthic macroinvertebrates. Because of its tendency to fragment, *Melosira* does not tend to reach as high densities or biomass as other more resistant types (for example, *Cladophora* or *Stigeoclonium*) in disturbed habitats.

Table 8. Dominant algal taxon (by cell density) at each site, dominant diatom taxon, and diatom water-quality indicator classification, Willamette River basin and surrounding area, Oregon and Washington.

[Sites are sorted by the urban intensity index (UII). Shading indicates sites with UII greater than 25. Water-quality indicator from Porter (2008). **Abbreviations:** TN, total nitrogen; DO, dissolved oxygen; SW, southwest; OR, Oregon, WA, Washington; DIN, dissolved inorganic nitrogen. **Symbols:** >, greater than]

Site name	UII	Dominant algal taxon		Dominant diatom taxon	
		Division	Scientific name	Scientific name	Diatom water-quality indicator
Beaverton Creek near SW 216th Avenue, near Orenco, OR	100	Red algae	Unknown Rhodophyte Florideophycidae	*Gomphonema kobayasii*	Preference for high TN
Claggett Creek at Keizer, OR	100	Red algae	Unknown Rhodophyte Florideophycidae	*Gomphonema kobayasii*	Preference for high TN
Fanno Creek at Durham, OR	96	Blue-green algae	*Leptolyngbya* sp.	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Kellogg Creek at Milwaukie, OR	88	Blue-green algae	*Homoeothrix janthina*	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Pringle Creek at Salem, OR	88	Blue-green algae	*Homoeothrix janthina*	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Amazon Creek near Danebo Road, at Eugene, OR	77	Blue-green algae	*Leptolyngbya* sp.	*Amphora pediculus*	Eutrophic/moderate DO (>75 percent)
Tryon Creek below Nettle Creek, near Lake Oswego, OR	72	Blue-green algae	*Homoeothrix janthina*	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Curtin Creek near Vancouver, WA	69	Blue-green algae	*Homoeothrix janthina*	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Johnson Creek at Circle Avenue, OR	59	Red algae	Unknown Rhodophyte Florideophycidae	*Gomphonema kobayasii*	Preference for high TN
Battle Creek near Turner, OR	58	Blue-green algae	*Leptolyngbya* sp.		Preference for high DIN/ moderate DO (>75 percent)
Rock Creek at Quatama Road, near Hillsboro, OR	51	Blue-green algae	*Phormidium autumnale*	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Whipple Creek near Salmon Creek, WA	49	Red algae	Unknown Rhodophyte Florideophycidae	*Cocconeis placentula* var. lineata	Eutrophic/low DO (>50 percent)
Chicken Creek near Sherwood, OR	45	Red algae	Unknown Rhodophyte Florideophycidae	*Nupela* sp.	Unknown
North Fork Deep Creek at Barton, OR	39	Blue-green algae	*Porphyrosiphon martensianus*	*Achnanthes subhudsonis* var. kraeuselii	Unknown
Oak Creek at Corvallis, OR	39	Red algae	Unknown Rhodophyte Florideophycidae	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)

Table 8. Dominant algal taxon (by cell density) at each site, dominant diatom taxon, and diatom water-quality indicator classification, Willamette River basin and surrounding area, Oregon and Washington..—Continued

[Sites are sorted by the urban intensity index (UII). Shading indicates sites with UII greater than 25. Water-quality indicator from Porter (2008). **Abbreviations:** TN, total nitrogen; DO, dissolved oxygen; SW, southwest; Ave., avenue; OR, Oregon, WA, Washington; DIN, dissolved inorganic nitrogen. **Symbols:** >, greater than]

Site name	UII	Dominant algal taxon		Dominant diatom taxon	
		Division	Scientific name	Scientific name	Diatom water-quality indicator
Tickle Creek near Boring, OR	32	Blue-green algae	*Homoeothrix janthina*	*Achnanthes subhudsonis* var. kraeuselii	Unknown
Chehalem Creek at Newberg, OR	29	Blue-green algae	*Homoeothrix janthina*	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Silk Creek near Cottage Grove, OR	24	Blue-green algae	Unknown Cyanophyte	*Rhoicosphenia abbreviata*	Eutrophic/moderate DO (>75 percent)
Rock Creek near Battleground, WA	23	Blue-green algae	*Aphanocapsa* sp.	*Achnanthidium minutissimum*	Preference for high DIN/high DO (near 100 percent)
Salmon Creek near Battleground, WA	20	Blue-green algae	*Homoeothrix janthina*	*Achnanthidium* sp. 10	Unknown
Deep Creek near Sandy, OR	17	Diatom	*Achnanthes subhudsonis* var. kraeuselii	*Achnanthes subhudsonis* var. kraeuselii	Unknown
Nate Creek near Colton, OR	15	Blue-green algae	*Homoeothrix janthina*	*Achnanthidium* sp. 10	Unknown
Milk Creek at Camp Adams, OR	12	Blue-green algae	*Phormidium autumnale*	*Gomphonema* sp. 2	Unknown
North Yamhill Creek near Yamhill, OR	8	Blue-green algae	Unknown Cyanophyte	*Achnanthidium minutissimum*	Preference for high DIN/high DO (near 100 percent)
South Scappose Creek at Scappose, OR	8	Blue-green algae	*Homoeothrix janthina*	*Gomphonema kobayasii*	Preference for high TN
Lost Creek near Dexter, OR	6	Blue-green algae	*Homoeothrix janthina*	*Gomphonema rhombicum*	Unknown
Iler Creek near Forest Grove, OR	4	Blue-green algae	*Homoeothrix janthina*	*Cocconeis placentula* var. euglypta	Eutrophic/low DO (>50 percent)
East Fork Dairy Creek near Meacham Corner, OR	0	Blue-green algae	Unknown Cyanophyte	*Achnanthes subhudsonis* var. kraeuselii	Unknown

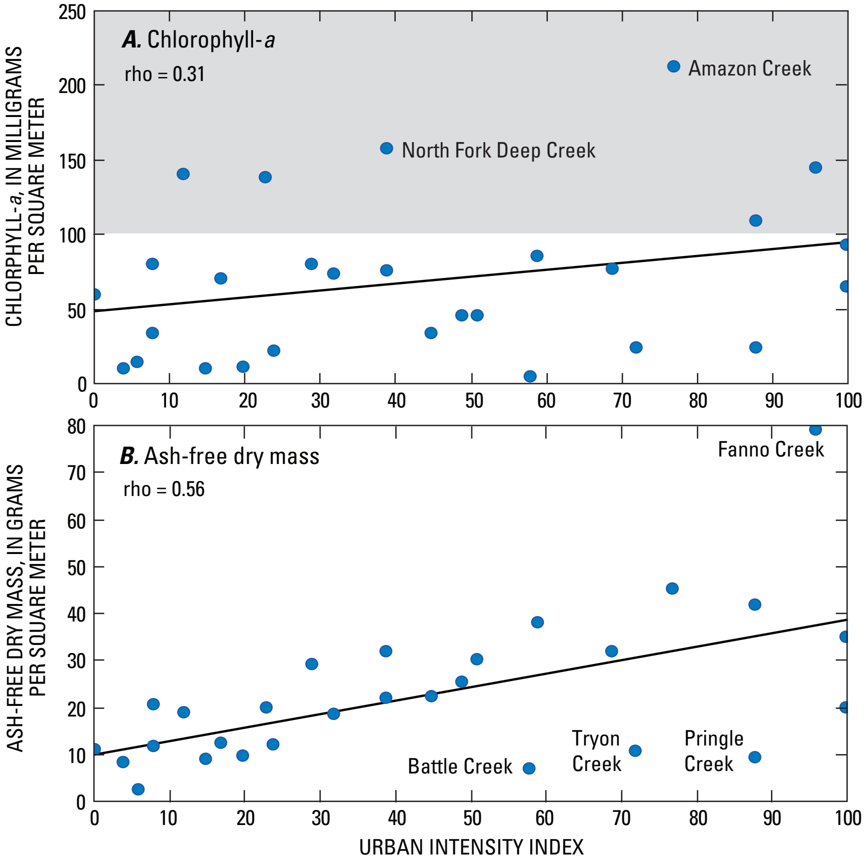


Figure 14. Relation between the urban intensity index (UII) and (*A*) chlorophyll-*a* and (*B*) ash-free dry mass, Willamette River basin and surrounding area, Oregon and Washington. (Shading represents concentrations of chlorophyll-*a* greater than 100 mg/m^2).

Multivariate Analysis of Diatom Assemblages

A number of environmental factors such as climate, geology, water-quality, habitat conditions, and anthropogenic disturbances (Biggs, 1990) can influence algal assemblages. In this study, diatom assemblage structure (axes scores from nMDS ordinations) were not significantly correlated (rho less than 0.2) to any of the urban indicators including road and population density, percentage of impervious area and urban land, or the UII. Additional multivariate analyses were conducted to identify which environmental variables (or combinations) explained the most variation in the diatom assemblage structure using the BEST routine in PRIMER. Variables included habitat parameters (water depth, velocity, and embeddedness), disturbance indicators (benthic macroinvertebrate grazers and a hydrologic variability index), light availability (open canopy), and water-quality measures (nutrients, DOC, pH, DO, and specific conductance). The best combination of variables—DOC, pH, Rb-flash and benthic macroinvertebrate scraper density—explained 68 percent of the variation in the diatom assemblage.

DOC, which was negatively correlated with DO (fig. 15), explained 44 percent of the variation in the diatoms assemblage structure among all sites. The highest individual rho values were those associated with habitat and channel hydraulics (percentage run habitat, Froude number, and maximum depth, rho = 0.47; average substrate embeddedness, rho = 0.32) and water chemistry (high-flow period specific conductance, rho =0.43; summer total phosphorus, rho = 0.33; summer particulate nitrogen, rho = 0.33; summer minimum water temperature, rho = 0.33). Habitat and hydraulic conditions can alter the velocity regime for benthic algae, which can affect its overall growth form and profile (Hoagland and others, 1982), which is consistent with the influence of Froude number and Rb-flash on the diatom assemblage structure. In these streams, the higher amount of run habitat (and gradient) also might be contributing to higher sedimentation, leading to higher average substrate embeddedness. The water-quality variable with the highest rho value was specific conductance. Specific conductance often is used as a broad measure of anthropogenic influence, but is also affected by dilution (and watershed size), as well as

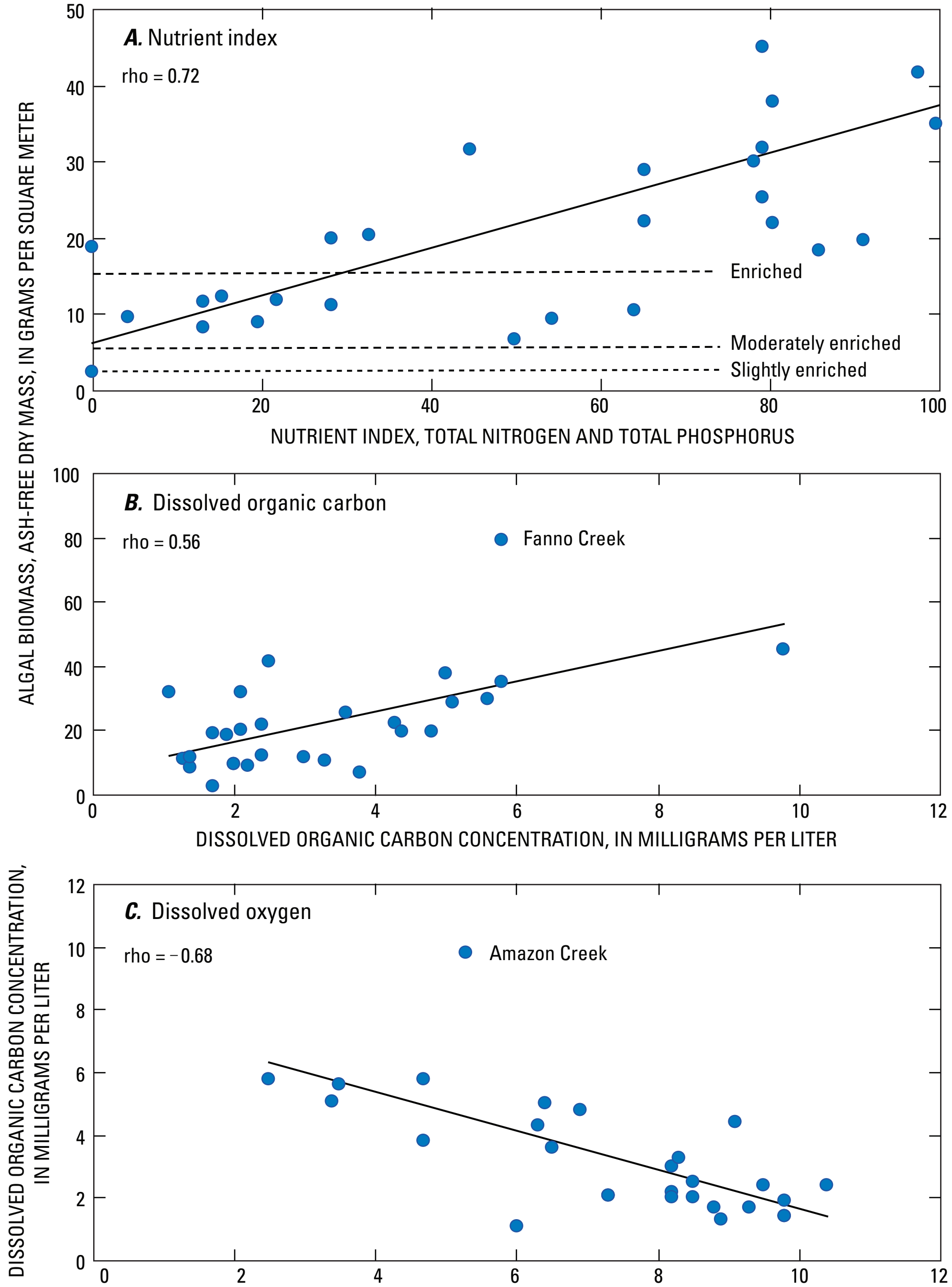


Figure 15. Relations between ash-free dry mass and (*A*) nutrient index and (*B*) concentrations of dissolved organic carbon, and (*C*) dissolved organic carbon and concentrations of dissolved oxygen, Willamette River basin and surrounding area, Oregon and Washington.

natural factors such as soil and geology. Specific conductance has been shown to correlate well with algal assemblages in other studies in Oregon (Walker and Pan, 2006), other EUSE study areas (Potapova and others, 2005), and in Australia (Newall and Walsh, 2005). Correlations between specific conductance and anthropogenic influences can be stronger than nitrogen and phosphorus concentrations in streams with significant algal growths because of the nutrient uptake effect, which can lower nutrient levels substantially during periods of active growth.

Response in Algal Metrics to Urban Intensity Index and Select Environmental Variables

Two algal metrics were correlated to the UII, including percentage of diatoms requiring high DO concentrations (nearly saturated) and, to a lesser degree, percentage of eutrophic (high-nutrient indicator) algae (fig. 16). Algal metrics also indicate that nutrient and sediment enrichment have measurable effects on the diatom assemblage structure in these streams, with eight metrics having significant correlations with either the UII or other environmental variable (table 9). The highest correlation coefficients (rho values) occurred between algal metrics and water-quality variables, including nutrients, DOC, and DO, and measures of algal biomass, especially AFMD (table 9).

The percentage of high-nutrient indicators (eutrophic diatoms) was strongly correlated to specific conductance (rho = 0.67) and moderately correlated to soluble reactive phosphorus (rho = 0.65), total phosphorus (rho = 0.55), and the nutrient index (rho = 0.52) (table 9). Another high-nutrient indicator metric (nitrogen heterotrophic taxa)—those that can use organic forms of nitrogen (organic nitrogen)—also were significantly correlated with concentrations of total nitrogen and total phosphorus (rho = 0.62 and 0.69, respectively) and algal biomass (AFDM: rho = 0.73; chlorophyll-*a*: rho = 0.69) (table 9).

Algal metrics also showed the effects of depressed levels of DO in these streams that can result from bacterial respiration associated with decomposition of organic matter. For example, low-oxygen indicating taxa tolerant of depressed DO (10–30 percent saturation, or less [van Dam and others, 1994]) were positively correlated with total phosphorus (rho = 0.62), DOC (rho = 0.69), and benthic algal biomass (AFDM, rho = 0.63) (table 9). In contrast, high oxygen indicator diatoms had negative correlations for most water-quality variables, particularly specific conductance and soluble reactive phosphorus (rho = -0.74 and -0.62, respectively). Additionally, the percentage of taxa associated with high levels of organic enrichment (*a*-mesosaprobic diatoms) was significantly correlated with concentrations of total phosphorus (organic nutrient: rho = 0.64) (table 9). These taxa tolerate depressed DO levels (10–70 percent saturation) and are associated with biological oxygen demand (BOD) levels of 4–22 mg/L (van Dam and others, 1994).

The percentage of diatoms tolerant of nutrient and organic pollution (Bahls, 1993) were similarly positively correlated to total phosphorus and total nitrogen concentrations (tolerant taxa: rho = 0.67 and 0.71, respectively) and algal biomass (AFDM: rho = 0.66; chlorophyll-*a*: rho = 0.62). The percentage of pollution sensitive diatoms, however, showed the opposite pattern and was negatively correlated with TP and TN (sensitive

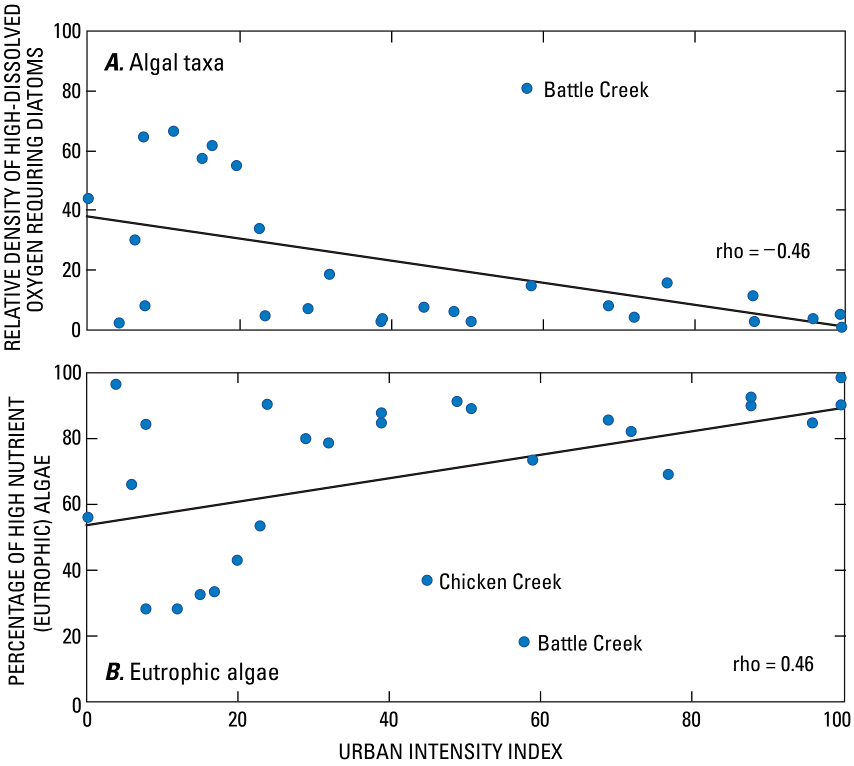


Figure 16. Relations between urban intensity index (UII) and (*A*) percentage of algal taxa requiring high levels of dissolved oxygen, and (*B*) relative density of eutrophic algae, Willamette River basin and surrounding area, Oregon and Washington.

Table 9. Spearman's rank correlation coefficients (rho values) between diatom algal metrics and the urban intensity index and select environmental variables, Willamette River basin and surrounding area, Oregon and Washington.

[See appendix A for definitions of environmental variables. Average concentrations were used for TN, NO_2+NO_3, total phosphorus, soluble reactive phosphorus, specific conductance, SO_4, and DOC. Correlation coefficients were considered strong when absolute value $\geq$ 0.66 (bolded and shaded) and moderate when 0.66 > *rho* $\geq$ 0.50 (bolded). **Nutrient, nitrogen, and oxygen taxa:** van Dam and others (1994). High nutrient indicating (eutrophic) taxa require high nutrient levels. Nitrogen heterotrophs–taxa may use organic nutrient forms. High organic taxa-*α*-meso/polysaprobous–taxa indicative of depressed dissolved oxygen levels (10–70 percent) and elevated biological oxygen demand (4–22 mg/L). Brackish water–taxa tolerate elevated levels of dissolved ions. Low oxygen–taxa tolerant of low dissolved oxygen levels. High oxygen–taxa require high dissolved oxygen levels. **Pollution,** Bahls (1993): **tolerant**–taxa generally tolerant of nutrient and organic enrichment; **sensitive**–taxa generally sensitive to nutrient and organic enrichment. **Silt index**: calculated by Sprouffske and others, 2006. Sum of motile *Navicula* and *Nitzschia* diatom taxa. **Abbreviations:** mg/L, milligram per liter; nd, no data]

Environmental variables	Diatom metric							
	High indicating taxa			Oxygen indicating taxa		Pollution		Silt index
	Nutrient (eutrophic)	Organic enrichment	Organic nitrogen	Low	High	Tolerant taxa	Sensitive taxa	
Urban intensity index (UII)	0.46	**0.52**	0.38	0.33	-0.46	0.36	-0.45	0.40
Total nitrogen (TN)	.37	.47	**.62**	.44	-.27	**.71**	**-.62**	**.50**
Nitrite+nitrate (NO_2+NO_3)	.28	.24	.41	.18	-.15	**.63**	-.47	.44
Total phosphorus (TP)	**.55**	**.64**	**.69**	**.62**	**-.57**	**.67**	**-.68**	**.70**
Soluble reactive phosphorus (SRP)	**.65**	.44	**.57**	.42	**-.62**	**.59**	**-.51**	**.62**
Nutrient index	**.52**	**.54**	**.65**	**.52**	-.44	**.70**	**-.63**	nd
Specific conductance	**.67**	**.52**	**.51**	.48	**-.74**	**.50**	**-.50**	**.63**
Summertime dissolved oxygen (DO)	-.20	-.45	-.27	-.47	.28	-.36	.46	-.39
Summertime minimum water temperature	.41	**.53**	**.51**	**.51**	-.39	**.51**	**-.61**	**.52**
Sulfate (SO_4)	**.53**	.45	**.49**	.35	**-.52**	**.53**	-.44	**.60**
Dissolved organic carbon (DOC)	.25	**.70**	**.56**	**.69**		**.50**	**-.61**	**.58**
Chlorophyll-*a*	.11	.44	**.69**	.40	-.08	**.62**	**-.56**	**.54**
Ash-free dry mass (AFDM)	.29	**.63**	**.73**	**.63**	-.31	**.66**	**-.69**	**.69**

taxa: rho values = -0.68; and -0.62, respectively) and algal biomass (AFDM: rho = -0.69; chlorophyll-*a*: rho = -0.56). Lastly, the Silt Index—the percentage of motile diatom genera *Navicula* and *Nitzschia*—was positively correlated with total phosphorus and AFDM (table 9). These organisms can thrive in streams affected by siltation because they can move out of the sediments to the surface where light levels are higher.

Taken together, the algal data show that diatom assemblages are affected by variations in streamflow, grazing by herbivorous benthic invertebrates, and processes relating to DOC (organic matter formation from excessive nutrients and high water temperature and decomposition, and subsequent effects of algal and bacterial metabolism on concentrations of DO). The positive correlation between benthic organic matter (AFDM) and the UII indicate that urbanization increases the amount of algae and other organic matter in streams through nutrient and (or) organic enrichment. DO is an important factor for important fish such as trout and salmon, which require relatively high levels of DO for survival and reproduction.

Benthic Macroinvertebrate Assemblages

One-hundred thirty-nine unique benthic macroinvertebrate taxa were identified in the 28 RTH samples (table 10 and table A10). The most taxa (52) was for the insect order Diptera, with 37 from one dipteran family (Chironomidae), commonly known as midges. Diptera made up one-quarter of the total number of taxa collected, and had the highest taxa richness per family or order, by far. EPT orders—Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) had 13, 10, and 19 taxa per respective order. There were 12 taxa within the Coleoptera order (beetles), 2 taxa in Odonata (dragonflies and damselflies), and 1 each in Lepidoptera (butterflies and moths) and Megaloptera (dobsonflies). In addition to these insects, 29 noninsect taxa were spread among 17 orders, including snails, clams, aquatic worms, amphipods, and mites (table 10).

Only *Simulium caadense* (a dipteran blackfly) and *Fluminicola* (a gastropod snail) reached maximum single-sample abundances greater than 11,000 specimens per m^2.

Table 10. Number of benthic macroinvertebrate taxa and maximum abundance per insect order or noninsect group, Willamette River basin and surrounding area, Oregon and Washington.

[**Abbreviation:** m^2, square meter]

Insect order/ noninsect group	Number of unique taxa	Most abundant taxon	Maximum abundance (m^2)
Insects			
Ephemeroptera	13	*Baetis tricaudatus*	3,082
Plecoptera	10	*Zapada cinctipes*	4,081
Trichoptera	19	*Cheumatopsyche* sp.	3,467
Diptera	52	*Simulium canadense*	12,306
Chironomidae[1]	37	*Cricotopus bicinctus group*	3,303
Coleoptera	12	*Optioservus* sp.	1,349
Lepidoptera	1	*Lepidoptera*	64
Megaloptera	1	*Sialis* sp.	40
Odonata	2	*Gomphidae*	113
Total insects	110		
Noninsects			
Amphipoda	3	*Hyalella azteca*	1,401
Oligochaeta	5	Tubificidae	2,129
Mollusca	10	*Fluminicola* sp.	11,419
Other non-insects	11	Acari	988
Total noninsects	29		
Total number of taxa	139		

[1] The Chironomidae value is included in the Order Diptera and is not added for total insects.

Other major insect and noninsect orders had maximum abundances of between 1,300 and 4,100 specimens per sample. The noninsect Acari (Hydracarina, or water mites) and *Simulium canadense* (Diptera) were the most common taxa collected, occurring at 27 out of 28 sites (96 percentage occurrence; table 11), in addition, four of the top six most common taxa were other noninsects: Acari, *Juga* sp. (a snail), *Dero* sp. (Oligochaete worm), and Lumbriculidae (Oligochaete worm). Of the 22 taxa with at least 50 percent occurrence, 9 were noninsects, 6 were Diptera (5 chironomid midges and one blackfly, *Simulium*), 3 were Ephemeroptera, and 2 each were from Trichoptera and Coleoptera orders (table 11). Eighteen of these 22 taxa were considered moderately to highly tolerant of poor water-quality conditions, although 4 taxa (*Paraleptophlebia* sp., *Zapada cinctipes*, *Rhithrogena* sp., and *Ceratopsyche cockerelli*) were considered moderately to relatively sensitive.

Benthic Macroinvertebrate Metrics in Relation to Urban Intensity Index

The benthic macroinvertebrate metric “percent dominance” (percentage abundance of the maximum single taxon) has been considered a good bioindicator by some researchers (Barbour and others, 1999); however, in this and other recent studies, it does not correlate well with disturbance in this geographic region. In this study, percent dominance ranged from 14 percent to 67 percent, yet it only had a correlation to the UII of rho = 0.31. However, the tolerance values of the single dominant taxa did show a good relation to the UII. A list of sites, sorted by UII (table 12), showed that the dominant taxa of the 17 sites with a UII greater than 25 had tolerance values between 7 and 10 (average 8), as determined by the USEPA tolerance scale (least to most tolerant—0 to 10). Additionally, those sites with UII greater than 25 had, on average, EPT richness of 4 taxa totaling 15 percent. On the other hand, sites with a UII less than 25 had tolerance values for their dominant taxa of between 3 and 8 (average 5), with much greater numbers of EPT taxa (average of 15 EPT taxa or a percent EPT richness of 44 percent). As a result, although percent dominance as a metric by itself did not correlate well to disturbance, interpreting ecological characteristics of the single dominant taxa among sites, such as USEPA tolerance values and optima, was useful (table 12). Looking at all sites instead of just the end members, there also was a strong negative correlation between EPT richness and UII (rho = -0.75; fig. 17) that reflects this large decrease in EPT taxa from the low to high urban sites.

Cuffney and others (2005) compared benthic macroinvertebrate metrics from three urban studies for two site groupings with different urban intensities: (1) most highly urban sites sampled (UII ≥ 70) and (2) sites near reference condition (UII ≤ 10). They detected large differences between these two groupings in the richness and density of major benthic macroinvertebrate metrics including all taxa, EPT taxa only, Diptera, Chironomidae, and noninsects. Results from this study were similar, with an average increase of 12 EPT taxa and 32 percent EPT richness from the high urban group to the near reference condition group (table 13). However, unlike Cuffney and others (2005), who showed a large increase in total richness (+25 taxa), we detected only a small increase in total taxa richness (an average increase of 5 taxa). In this study, the large increase in “EPT percent richness” was in addition to a large increase in average abundance of intolerant macroinvertebrates (+3,848) and Ephemeroptera (+3,111). There also was a large decrease in percentage of noninsect richness (-31 percent) and abundance of tolerant taxa (-48 percent). Plecoptera are one of the most sensitive aquatic insect orders and, on average, almost no Plecoptera were detected at the highly urbanized sites, yet on

Table 11. Commonly observed benthic macroinvertebrate taxa and tolerance values, Willamette River basin and surrounding area, Oregon and Washington.

[Taxa sorted in order of decreasing frequency of occurrence. **Insect order and noninsect group**: Taxa occurs in more than 50 percent of streams. **Abbreviation:** PNW, Pacific Northwest]

Insect order and noninsect group	Taxa	Number of streams	Percent of sites	PNW tolerance value
Noninsect (water mite)	Acari	27	96	6
Diptera	*Simulium canadense*	27	96	6
Noninsect (snail)	*Juga* sp.	25	89	7
Ephemeroptera	*Baetis tricaudatus*	23	82	7
Noninsect (worm)	*Dero* sp.	22	79	10
Noninsect (worm)	Lumbriculidae	20	71	8
Trichoptera	*Cheumatopsyche* sp.	19	68	8
Ephemeroptera	*Paraleptophlebia* sp.	19	68	5
Diptera (Chironomidae)	*Polypedilum* sp.	19	68	6
Diptera (Chironomidae)	*Thienemannimyia* group sp.	17	61	6
Diptera (Chironomidae)	*Rheotanytarsus* sp.	16	57	6
Diptera (Chironomidae)	*Eukiefferiella* sp.	16	57	8
Diptera (Chironomidae)	*Cricotopus bicinctus* group	16	57	7
Coleoptera	*Optioservus* sp.	16	57	9
Coleoptera	*Zapada cinctipes*	16	57	4
Noninsect (snail)	*Ferrissia* sp.	16	57	7
Noninsect (amphipod)	*Crangonyx* sp.	15	54	8
Noninsect (worm)	Tubificidae	15	54	10
Noninsect (crayfish)	*Pacifastacus leniusculus*	15	54	7
Noninsect (snail)	*Fluminicola* sp.	15	54	7
Ephemeroptera	*Rhithrogena* sp.	15	54	3
Trichoptera	*Ceratopsyche cockerelli*	14	50	5

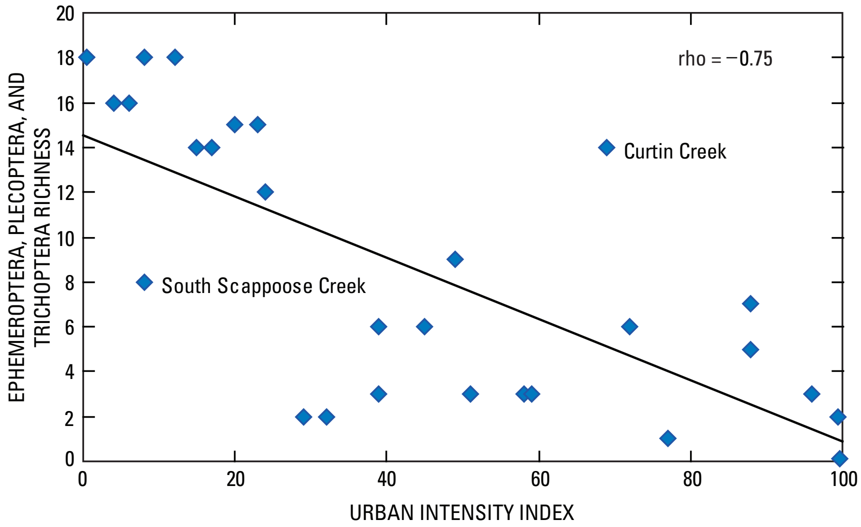


Figure 17. Relation between urban intensity index (UII) and number of benthic macroinvertebrate taxa (richness) in the Ephemeroptera, Plecoptera, and Trichoptera orders (EPT), Willamette River basin and surrounding area, Oregon and Washington.

Table 12. Single dominant benthic macroinvertebrate taxon at each site, taxon name, U.S. Environmental Protection Agency tolerance value, Ephemeroptera, Plecoptera, and Trichoptera richness, and richness percentage per site, Willamette River basin and surrounding area, Oregon and Washington.

[Sites are sorted by the urban intensity index (UII). Shading indicates sites with UII greater than 25. **Abbreviations:** EPT, Ephemeroptera, Plecoptera, and Trichoptera; USEPA, U.S. Environmental Protection Agency; SW, southwest; OR, Oregon; WA, Washington]

Site name	UII	Percent dominant taxon	Dominant taxon	USEPA tolerance value	EPT richness	EPT percent richness
Beaverton Creek near SW 216th Avenue, near Orenco, OR	100	27	*Baetis tricaudatus*	7	2	11
Claggett Creek at Keizer, OR	100	42	Tubificidae	10	0	0
Fanno Creek at Durham, OR	96	57	*Cheumatopsyche* sp.	8	3	11
Kellogg Creek at Milwaukie, OR	88	27	*Cheumatopsyche* sp.	8	7	21
Pringle Creek at Salem, OR	88	49	*Simulium canadense*	7	5	17
Amazon Creek near Danebo Road, at Eugene, OR	77	35	*Cricotopus bicinctus* group	7	1	4
Tryon Creek below Nettle Creek, near Lake Oswego, OR	72	30	*Baetis tricaudatus*	7	6	17
Curtin Creek near Vancouver, WA	69	16	*Cheumatopsyche* sp.	8	14	36
Johnson Creek at Circle Avenue, OR	59	29	*Cheumatopsyche* sp.	8	3	12
Battle Creek near Turner, OR	58	51	*Cheumatopsyche* sp.	8	3	14
Rock Creek at Quatama Road, near Hillsboro, OR	51	37	*Cheumatopsyche* sp.	8	3	10
Whipple Creek near Salmon Creek, WA	49	16	*Optioservus* sp.	9	9	27
Chicken Creek near Sherwood, OR	45	38	*Cheumatopsyche* sp.	8	6	24
North Fork Deep Creek at Barton, OR	39	34	*Baetis tricaudatus*	7	3	11
Oak Creek at Corvallis, OR	39	31	*Ferrissia* sp.	7	6	21
Tickle Creek near Boring, OR	32	67	*Simulium canadense*	7	2	11
Chehalem Creek at Newberg, OR	29	51	*Fluminicola* sp.	7	2	7
Silk Creek near Cottage Grove, OR	24	28	*Simulium canadense*	7	12	34
Rock Creek near Battleground, WA	23	14	*Paratanytarsus* sp.	6	15	36
Salmon Creek near Battleground, WA	20	27	*Rhithrogena* sp.	3	15	54
Deep Creek near Sandy, OR	17	23	*Baetis tricaudatus*	7	14	41
Nate Creek near Colton, OR	15	30	*Rhithrogena* sp.	3	14	50
Milk Creek at Camp Adams, OR	12	23	*Cheumatopsyche* sp.	8	18	56
North Yamhill Creek near Yamhill, OR	8	36	*Ceratopsyche cockerelli*	5	18	51
South Scappose Creek at Scappose, OR	8	20	*Rhithrogena* sp.	3	8	31
Lost Creek near Dexter, OR	6	30	*Rhithrogena* sp.	3	16	50
Iler Creek near Forest Grove, OR	4	26	*Rhithrogena* sp.	3	16	37
East Fork Dairy Creek near Meacham Corner, OR	0	18	*Zapada cinctipes*	4	18	47
Average of sites greater than UII of 25		37		8	4	15
Average of sites less than UII of 25		25		5	15	44

Table 13. Comparison of average benthic invertebrate abundance and richness metrics for high- and low-urban streams, Willamette River basin and surrounding area, Oregon and Washington.

[**Abbreviations:** UII, urban intensity index; EPEM, Ephemeroptera; PLECO, Plecoptera; EPT, Ephemeroptera, Plecoptera, and Trichoptera. **Symbols:** >, greater than; <, less than]

Urban intensity index	Total taxa richness	EPEM abundance	PLECO percent abundance	EPT percent richness	EPT richness	Noninsect percent richness	Intolerant abundance	Tolerant percent abundance
UII < = 10	30	3,622	14	43	15	16	3,891	25
UII > = 70	25	511	0	11	3	47	43	73
Difference	**5**	**3,111**	**14**	**32**	**12**	**-31**	**3,848**	**-48**

average, 14 percent abundance was detected at the sites near reference condition. Total taxa richness did not show a strong relation to urbanization in the Willamette Valley, even though richness of individual groups like EPT and noninsects had a strong relation to the UII. This indicates that there is specie replacement along the gradient, such that as sensitive EPT taxa drop out as urbanization increases noninsects and chironomid taxa take their place and total taxa richness remains relatively the same. Therefore, like the metric percent dominance mentioned previously, total taxa richness does not work well as a metric indicative of disturbance in this region even though it often is useful in other geographic regions.

Many benthic macroinvertebrate metrics had strong correlations to the UII. The three greatest rho values were for Ephemeroptera richness (negative), Plecoptera richness (negative), and the abundance of tolerant taxa (positive; table 14). Spearman correlation coefficients for these three benthic macroinvertebrate metrics and the five urban indicators were all greater than ±0.69, with the strongest positive correlation between tolerant taxa and the UII (0.79) and the strongest negative between EPEM richness and POPDEN00 (-0.79; table 14). Many benthic macroinvertebrate metrics also had relatively strong correlation values with selected environmental setting metrics, including measures of soil erosion potential, elevation, precipitation, watershed slope, and percentage of low elevation flat land in the watershed (table 14). Urban and agricultural land use development follows the natural topography in the Willamette Valley; a higher percentage of development is in the flatter low-elevation valley and less in the higher elevation foothills. Cuffney and others (2005) determined strong correlations for similar environmental setting variables with benthic macroinvertebrate metrics, but only for the more mountainous Salt Lake City region and not for the Boston or Birmingham areas. In the Willamette River basin and surrounding area, a number of benthic macroinvertebrate metrics had their strongest correlation coefficients to water-chemistry metrics, such as TP, total insecticide and total pesticide concentration, PTI, TEQ, and the Pyrene Index. Most Spearman correlation coefficients between benthic macroinvertebrate richness metrics and the aforementioned water-chemistry metrics were greater than 0.70 (table 14). The four strongest correlations were between percent Diptera richness (not including chironomid midges) and the Pyrene Index (rho = 0.88) and the TEQ (0.85), and between percent richness of tolerant taxa and the TEQ (0.87), and between the EPT: Chironomid ratio and the total insecticide concentration (-0.85; table 14). These strong correlation values between water-chemistry metrics and benthic macroinvertebrate metrics are similar to those published by Cuffney and others (2005), and indicate that one effect of pesticides and other potentially toxic compounds is a reduction in the number of sensitive insect taxa in favor of more tolerant chironomid midge larvae.

A shift in the benthic macroinvertebrate assemblage toward less palatable organisms such as worms (Oligochaetes), or snails potentially could affect fish assemblages. Any reduction in EPT insect abundance or taxa richness could have implications for salmonids and other fish in this region because EPT taxa are important contributors to aquatic food webs, linking algae with fish. EPT taxa include herbivorous caddisflies and mayflies, which play an important role in food webs by grazing algae. The EPT taxa typically emerge into flying adults in a chronologic sequence that lasts nearly year-round, in a pattern predictable to the local angler and resident fish. Reductions in EPT taxa could, reduce food available for fish that may lead to reductions in production or changes in species composition indirectly, in addition, stream conditions such as temperature, DO, or other factors that affect macroinvertebrates may also directly affect the natural fish assemblage.

Multivariate Analysis of Benthic Macroinvertebrate Assemblages

Ordination analysis took advantage of the full species assemblage at each site to determine patterns among sites based on the biological data. This approach provided a more complete picture compared to analysis of individual benthic macroinvertebrate metrics, which examined selected components of the assemblage. The first nMDS ordination axis scores summarizes the major variation among sites as revealed by the full benthic macroinvertebrate species data (see Methods: Data Reduction and Analysis for explanation of ordinations), the scores reveal how the sites spread in a 2-dimensional plot based on the species occurring at each site. Therefore, sites that plot close to each other are similar in species composition, whereas sites that plot far apart from one another are very different in species composition. The first ordination axis scores were negatively correlated to the UII with a consistent and fairly even distribution of points, whereas the percentage of low elevation flat land in the watershed, shown to have relatively high correlations only to a few invertebrate metrics, did not correlate as well (figs. 18*A* and *C*), nor did the points spread consistently over the range of ordination scores. The ordination axis scores on the other hand, also had strong correlations to many of the same water-quality parameters as did the individual metrics (fig. 18*B*) and the correlation values were within a similar range as the metrics (TEQ; rho = -0.87; fig. 18*D*). The PRIMER BEST routine identified six variables—TEQ, sum of total pesticides, average embeddedness, DO or percent riffle habitat (surrogates for each other), 7-day average water temperature, and the UII or percentage of urban plus agricultural land (surrogates for each other)—that explained about 65 percent of the variation in the benthic macroinvertebrate assemblages among all sites.

Table 14. Correlation between selected benthic macroinvertebrate metrics and environmental variables, Willamette River basin and surrounding area, Oregon and Washington.

[See appendix A for definitions of environmental variables. Correlation coefficients were considered strong when absolute value ≥ 0.66 (bolded and shaded) and moderate when 0.66 > rho ≥ 0.50 (bolded). **Abbreviations:** DO, dissolved oxygen; EPEM, Ephemeroptera; EPT, Ephemoroptera, Plecoptera, Trichoptera; PLECO, Plecoptera; ROADDEN, road density; SPMD, semipermeable membrane device; TEQ, toxic equivalent; nMDS + AFDM, nonmetric dimensional scaling + ash-free dry mass; mg/L, milligram per liter. **Symbols:** >, greater than; ≥, greater than or equal to]

Environmental variables	Invertebrate metrics														
	Ephemeroptera		EPT		Plecoptera		Non-chironomids	Tolerant or intolerant metrics				Noninsect metrics			Full invertebrate assemblage
	EPEM abun-dance	EPEM richness	EPT/ chironomid ratio	EPT richness	PLECO percent	PLECO richness	Nonmidge diptera percent richness	Intolerant abun-dance	Tolerant richness	Tolerant percent richness	Tolerant abun-dance	Amphipod percent	Noninsect percent richness	Oligochaete percent richness	nMDS Axis1 score
Urban indicator metrics															
Urban intensity index (UII)	**-0.72**	**-0.78**	**-0.71**	**-0.75**	**-0.70**	**-0.77**	**0.75**	**-0.76**	**0.74**	**0.74**	**0.79**	**0.68**	**0.76**	**0.74**	**-0.83**
Percent impervious surface	**-.66**	**-.76**	**-.70**	**-.72**	**-.67**	**-.75**	**.71**	**-.71**	**.71**	**.71**	**.75**	**.72**	**.72**	**.71**	**-.79**
POPDEN00	**-.69**	**-.79**	**-.74**	**-.77**	**-.69**	**-.78**	**.74**	**-.76**	**.77**	**.76**	**.78**	**.67**	**.74**	**.74**	**-.83**
Percent urban and agriculture	**-.66**	**-.74**	**-.69**	**-.72**	**-.66**	**-.74**	**.70**	**-.73**	**.69**	**.67**	**.74**	**.68**	**.72**	**.68**	**-.80**
ROADDEN	**-.63**	**-.72**	**-.67**	**-.67**	**-.67**	**-.69**	**.67**	**-.71**	**.67**	**.67**	**.73**	**.60**	**.67**	**.70**	**-.76**
Environmental setting metrics															
Mean soil erodibility	**-0.63**	**-0.64**	**-0.55**	**-0.60**	-0.44	**-0.60**	**0.66**	**-0.51**	**0.69**	**0.66**	**0.75**	**0.58**	**0.66**	**0.67**	**-0.64**
Minimum watershed elevation	.42	**.52**	.49	.43		**.53**	-.48	.38	**-.60**	**-.61**	**-.58**	**-.61**	-.44	**-.56**	.45
Percent flat and low elevation land in basin	**-.72**	**-.60**	**-.52**	**-.55**	-.44	**-.53**	**.55**	**-.57**	**.52**	**.56**	**.51**	**.69**	**.62**	**.52**	**-.69**
Annual precipitation	**.57**	**.57**	**.54**	**.57**	**.51**	**.59**	**-.62**	.44	**-.67**	**-.69**	**-.69**	**-.61**	**-.61**	**-.54**	**.63**
Mean percent watershed slope	.45	**.67**	**.58**	**.64**	**.63**	**.65**	**-.60**	**.63**	**-.55**	-.49	**-.61**	**-.69**	**-.65**	**-.55**	**.65**
Hydrologic variation metrics															
Number of falling events > 5×median (PeriodF5)	**-0.53**	**-0.55**	**-0.59**	**-0.55**	**-0.60**	**-0.56**	**0.62**	**-0.54**	**0.51**	**0.57**	**0.54**	0.44	**0.60**	**0.68**	**-0.62**
Number of falling events > 9×median (PeriodF9)	**-.57**	**-.59**	**-.58**	**-.51**	-.49	**-.52**	**.62**	**-.59**	**.51**	**.59**	**.57**	.36	**.56**	**.67**	**-.59**
Number of rising events > 5×median (PeriodR5)	-.45	**-.53**	**-.55**	**-.50**	**-.58**	**-.51**	**.57**	**-.51**	.47	**.53**	**.50**	.39	**.56**	**.60**	**-.56**
Richards-Baker Flashiness Index (Rb-flash)	**-.60**	**-.55**	**-.56**	**-.57**	**-.60**	**-.58**	**.58**	**-.64**	**.60**	**.55**	**.56**	.35	**.60**	**.52**	**-.64**
Water temperature metrics															
Minimum temperature (95th percentile)	-0.47	-0.48	-0.38	-0.44	-0.43	-0.38	**0.54**	-0.37	0.36	0.43	0.45	0.41	**0.59**	**0.67**	**-0.53**
Habitat metrics															
Mean embeddedness (riffle and runs)	**-0.60**	**-0.57**	-0.47	-0.49	-0.37	**-0.50**	0.40	-0.46	**0.55**	0.46	**0.67**	**0.55**	0.43	0.42	**-0.53**
Mean width/depth ration (riffle and runs)	.37	.37	.24	.28	.09	.26	-.23	.25	-.44	-.37	-.39	-.47	-.26	-.41	.30
Percent riffle habitat	**.64**	**.55**	.44	.46	.38	.47	-.41	.34	**-.54**	**-.51**	**-.58**	**-.58**	-.44	-.43	**.58**
Percent large substrate	.33	.21	.10	.22	-.03	.05	-.08	.13	-.24	-.18	-.22	-.11	-.11	-.16	.20
Mean habitat heterogeneity	**-.53**	-.34	-.22	-.35	-.08	-.16	.25	-.25	.39	.35	.38	.10	.30	.29	-.38

Table 14. Correlation between selected benthic macroinvertebrate metrics and environmental variables, Willamette River basin and surrounding area, Oregon and Washington.—Continued

[See appendix A for definitions of environmental variables. Correlation coefficients were considered strong when absolute value ≥ 0.66 (bolded and shaded) and moderate when 0.66 > rho ≥ 0.50 (bolded). **Abbreviations:** DO, dissolved oxygen; EPEM, Ephemeroptera; EPT, Ephemoroptera, Plecoptera, Trichoptera; PLECO, Plecoptera; ROADDEN, road density; SPMD, semipermeable membrane device; TEQ, toxic equivalent; nMDS + AFDM, nonmetric dimensional scaling + ash-free dry mass; mg/L, milligram per liter. **Symbols:** >, greater than; ≥, greater than or equal to]

Environmental variables	Invertebrate metrics														
	Ephemeroptera		EPT		Plecoptera		Non-chironomids	Tolerant or intolerant metrics				Noninsect metrics			Full invertebrate assemblage
	EPEM abundance	EPEM richness	EPT/chironomid ratio	EPT richness	PLECO percent	PLECO richness	Nonmidge diptera percent richness	Intolerant abundance	Tolerant richness	Tolerant percent richness	Tolerant abundance	Amphipod percent	Noninsect percent richness	Oligochaete percent richness	nMDS Axis1 score
Water-chemistry variables															
Instantaneous summer DO (mg/L)	**0.77**	**0.63**	**0.55**	**0.60**	0.45	**0.52**	**-0.58**	0.41	**-0.57**	**-0.56**	**-0.63**	-0.44	**-0.57**	-0.46	**0.69**
Average dissolved organic carbon	**-.70**	**-.69**	**-.74**	**-.72**	**-.72**	**-.73**	**.71**	**-.63**	**.70**	**.64**	**.69**	**.59**	**.67**	**.62**	**-.79**
Summer chlorophyll AFDM	**-.60**	**-.57**	**-.59**	**-.51**	-.42	**-.59**	.47	**-.54**	**.56**	**.55**	**.55**	**.52**	.44	.33	**-.57**
Average total suspended sediment	**-.58**	-.40	**-.50**	-.34	-.33	-.35	.43	-.25	.30	.28	.32	.25	.35	.30	-.48
Average sulfate concentration	**-.64**	**-.63**	**-.68**	**-.53**	-.48	**-.60**	**.58**	**-.58**	**.68**	**.66**	**.55**	**.74**	**.52**	**.56**	**-.62**
Average total nitrogen (TN)	**-.51**	**-.73**	**-.75**	**-.69**	**-.67**	**-.76**	**.58**	**-.68**	**.66**	**.55**	**.62**	**.66**	**.57**	.49	**-.69**
Average total phosphorus (TP)	**-.61**	**-.78**	**-.83**	**-.75**	**-.64**	**-.79**	**.65**	**-.64**	**.83**	**.74**	**.75**	**.72**	**.61**	**.56**	**-.72**
Total of insecticides (spring + summer)	**-.67**	**-.77**	**-.85**	**-.75**	**-.75**	**-.74**	**.71**	**-.72**	**.75**	**.65**	**.67**	**.54**	**.69**	**.66**	**-.80**
Total of pesticides (spring + summer)	**-.67**	**-.76**	**-.81**	**-.82**	**-.83**	**-.82**	**.78**	**-.75**	**.71**	**.65**	**.79**	.47	**.76**	**.56**	**-.85**
Pesticide Toxicity Index (PTI; spring + summer)	**-.54**	**-.71**	**-.80**	**-.81**	**-.81**	**-.80**	**.70**	**-.76**	**.75**	**.70**	**.67**	.42	**.69**	**.51**	**-.79**
TEQ (SPMD)	**-.77**	**-.80**	**-.77**	**-.79**	**-.69**	**-.81**	**.85**	**-.81**	**.80**	**.87**	**.79**	**.52**	**.83**	**.71**	**-.87**
Pyrene Index (SPMD)	**-.63**	**-.73**	**-.70**	**-.76**	**-.65**	**-.77**	**.88**	**-.68**	**.73**	**.82**	**.69**	**.52**	**.82**	**.69**	**-.77**

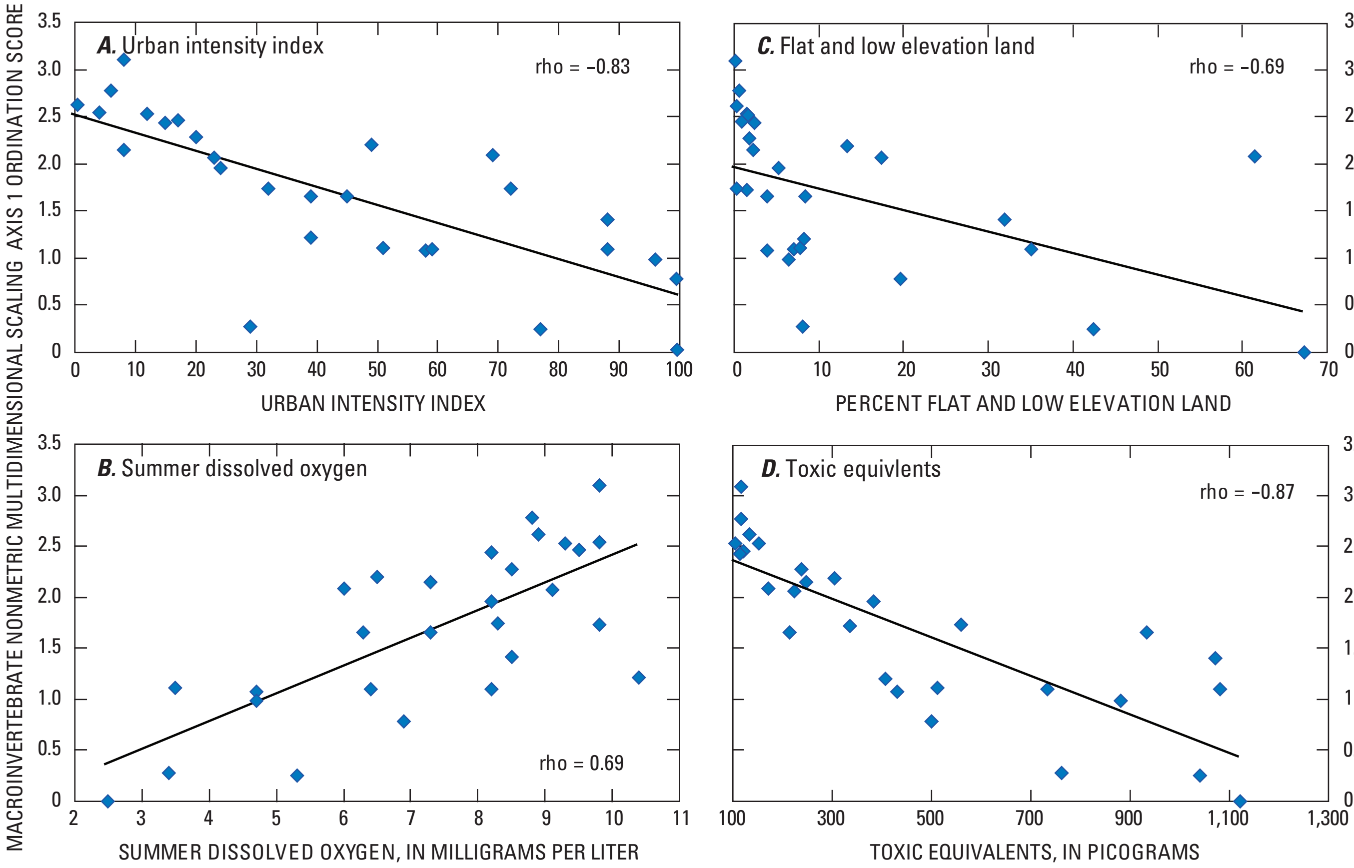


Figure 18. Benthic macroinvertebrate nonmetric dimensional scaling ordination axis 1 scores in relation to (*A*) urban intensity index (UII), (*B*) summer dissolved oxygen concentrations, (*C*) percentage of flat and low elevation land in watershed and (*D*) and toxic equivalents from semipermeable membrane devices, Willamette River basin and surrounding area, Oregon and Washington.

Although the first ordination axis used data from the complete benthic macroinvertebrate assemblage, the richness of EPT or Ephemeroptera metrics were strongly correlated with the nMDS axis score (rho greater than 0.90), which indicates that the first ordination axis largely described the same variation as the individual metrics, namely the change in richness of EPT or Ephemeroptera. This indicates that the disturbance gradient (UII) in the Willamette Valley was strong enough that differences among sites could be detected with only a part of the benthic macroinvertebrate assemblage. There is enough taxa diversity in the benthic macroinvertebrate data that part of the information is redundant. For example, EPT richness, a subset of the full species data set, could explain as much variation among sites as the full data (such as ordination axis).

Most benthic macroinvertebrate metrics showed linear responses to urbanization with no apparent threshold except, possibly, for EPT richness. EPT richness plotted against the UII showed a strong negative trend as urbanization increased and may have exhibited a threshold response near UII = 25 (fig. 17). All sites less than UII 25 had greater than 12 or more EPT taxa (average 15) except for South Scappoose Creek, whereas all sites greater than UII 25 had less than 9 EPT taxa (average 4), except for Curtin Creek (table 12). South Scappoose Creek likely has a lower EPT richness because it is a low gradient stream with minimal riffle habitat with potentially more urban influence than reflected by the UII score. Conversely, Curtin Creek had a greater abundance of EPT taxa than other streams greater than UII 25 because it had cold, clear summer flows due to a large amount of groundwater discharge upstream of the sampling site, thus offering better water quality habitat than what the UII would suggest. In addition, no insecticides were detected in Curtin Creek (table 4) and it had low TEQ and Pyrene Index values. As a result, Curtin Creek had remarkable numbers of EPT taxa and low percent taxa dominance even with little in-stream habitat. Cuffney and others (2005) determined that responses of benthic macroinvertebrate metrics in the pilot USGS EUSE study areas generally were linear and without thresholds, except for a few selected metrics for the Boston-area. No thresholds or initial resistance to the effects of urbanization for full assemblage measures or ordination axes were detected in any region (Cuffney and others, 2005).

Although there appeared to be a possible threshold in EPT richness at UII equal to 25, the apparent threshold was likely due to added agricultural land use in all sites greater than UII 25 than to any actual urban threshold. For example, at UII less than 25 the total percentage of urban plus agricultural land in the watershed was less than 16 percent (except for Deep Creek at 34 percent), yet immediately greater than a UII of 25, urban plus agricultural land increased markedly to between 53 and 98 percent (except for Oak Creek at 26 percent, table 1 and fig. 8). Therefore, any apparent threshold along the UII gradient was likely a threshold of the total of urban plus agricultural land use. However, the exact threshold is unknown because only two sites (Oak and Deep Creek) had urban plus agricultural land use percentages between 16 and 52 percent; therefore, there was not enough information in this data range to more fully evaluate thresholds. The plot of EPT richness and UII (fig. 17) indicates that if it exists, a threshold is at low values of urban plus agricultural land use, perhaps as low as 10 percent combined land use.

Although the streamflow, water temperature, and habitat measurements did not have as strong correlations as water-chemistry metrics to benthic macroinvertebrate metrics, they did have statistically significant values (greater than 0.60) for correlations of selected variables to a few metrics (table 14). The four hydrologic variables (PeriodF5, PeriodF9, PeriodR5 and Rb-flash) had correlations to a few benthic macroinvertebrate metrics greater than 0.60. For habitat measures, correlation values were this strong only for percentages of riffle and embeddedness correlated with Ephemeroptera abundance and tolerant abundance. Water temperature had only one correlation to benthic macroinvertebrate metrics greater than 0.60, with Oligochaete percent richness.

Fish Assemblages

Fish Metrics in Relation to Urban Intensity Index

Total fish richness ranged from 2 to 12 species, total abundance ranged from 52 to 672, and maximum relative abundance or percent dominance of any single species ranged from 20 to 98 percent among all sites (table 15). Sixty percent of the sites had six species or fewer, yet there was no strong correlation of number of fish species to total abundance. For example, the site with the highest number of species (12) had a total abundance of 163 (North Fork Deep Creek) and the site with the lowest numbers of species (2) had an abundance of 380 (Tyron Creek). Western streams naturally have relatively low fish species richness compared to streams east of the Rocky Mountains (Simon and Lyons, 1995; Meador and others, 2005), and as a result, fish species richness from western streams generally have not been a good bioindicator. For example, a poor relation of fish species richness to UII was determined in this study, yet Meador and others (2005) determined a strong relation between fish species richness and urbanization in the Boston and Birmingham areas. On the other hand, nonnative or invasive species are a more serious problem in western than eastern streams and nonnative fish were in approximately 50 percent of sites greater than a UII of 25, although only one occurrence was at a site less than 25 (table 15). Amazon Creek, with a UII of 77, contained the most nonnative species (five species) and highest percent abundance of nonnatives (98 percent) of any site. Claggett Creek, with a UII of 100, was the next highest with four nonnative species (19 percent abundance).

Although total species richness was not different between low and high UII sites, percentage of salmonids and nonnatives were different. Salmonids were present at 10 of 11 sites less than UII 25, whereas salmonids were present in only 4 of 17 sites greater than UII 25. No sites with salmonids had any nonnatives except one site, North Fork Deep Creek with 33 percent salmonids and 5 percent nonnatives. In this study, percent dominance (relative abundance) calculated from fish assemblage data had a strong curvilinear or possible threshold relation to the UII (rho = 0.67) where low urban sites (less than UII 25; table 15) had low percent dominance (average of 46 percent), although sites greater than UII 25 had average dominance values greater than 80 percent (fig. 19). The threshold for percent dominance at UII of 25 was equivalent to about 3–5 percent impervious surface, which was lower than most other thresholds previously reported for fish community metrics (Lyons and others, 1996; Wang and others, 2001). The apparent urban threshold likely was due to added agricultural land use in sites greater than UII 25 and therefore the threshold likely represents the effect from total watershed disturbance of urban plus agricultural land use and not just urbanization.

The fish index, which combined individual metrics of percentages of salmonids, reticulate sculpins, nonnatives, and natives (with salmonids and reticulates removed), had high correlation values to urban indicators (UII: rho = -0.68; table 16). The fish index also was strongly correlated (rho greater than 0.60) to PeriodF5 hydrology, embeddedness, width-depth ratio, riffle percentage, summer DO, DOC, specific conductance, sulfate concentration, and TEQ (table 16). The highest correlation values were between percentage of salmonids and summer DO (rho = -0.81) and percentage of riffle (rho = -0.78).

Table 15. Fish species richness, total abundance, percentages of dominance (single species), salmonids, and nonnative fish for 28 sites, Willamette River basin and surrounding area, Oregon and Washington.

[Sites are sorted by urban intensity index (UII). Shading indicates sites with UII greater than 25. **Abbreviations:** SW, southwest; OR, Oregon; WA, Washington]

Site name	UII	Species richness	Total abundance	Percent		
				Dominance	Salmonids	Nonnatives
Beaverton Creek near SW 216th Avenue near Orenco, OR	100	6	361	97	0	1
Claggett Creek at Keizer, OR	100	8	325	79	0	19
Fanno Creek at Durham, OR	96	6	586	91	0	0
Kellogg Creek at Milwaukie, OR	88	4	541	90	0	0
Pringle Creek at Salem, OR	88	9	600	88	0	0
Amazon Creek near Danebo Road at Eugene, OR	77	8	597	90	0	98
Tryon Creek below Nettle Creek, near Lake Oswego, OR	72	2	380	98	2	0
Curtin Creek near Vancouver, WA	69	5	52	79	17	0
Johnson Creek at Circle Avenue, OR	59	8	278	47	0	1
Battle Creek near Turner, OR	58	5	281	75	0	8
Rock Creek at Quatama Road near Hillsboro, OR	51	5	251	98		2
Whipple Creek near Salmon Creek, WA	49	3	162	83	0	0
Chicken Creek near Sherwood, OR	45	4	344	83	0	0
North Fork Deep Creek at Barton, OR	39	12	163	20	33	5
Oak Creek at Corvallis, OR	39	4	394	97	0	0
Tickle Creek near Boring, OR	32	8	672	77	18	0
Chehalem Creek at Newberg, OR	29	6	456	88	0	1
Silk Creek near Cottage Grove, OR	24	7	217	70	2	0
Rock Creek near Battleground, WA	23	6	395	55	25	0
Salmon Creek near Battleground, WA	20	9	183	52	5	0
Deep Creek near Sandy, OR	17	8	220	36	25	0
Nate Creek near Colton, OR	15	4	148	91	7	0
Milk Creek at Camp Adams, OR	12	11	301	36	6	0
North Yamhill Creek near Yamhill, OR	8	6	189	28	38	0
South Scappoose Creek at Scappoose, OR	8	7	96	44	0	1
Lost Creek near Dexter, OR	6	9	253	26	5	0
Iler Creek near Forest Grove, OR	4	6	150	39	35	0
East Fork Dairy Creek near Meacham Corner, OR	0	8	639	32	38	0
Average of sites greater than UII of 25		6	379	81	4	8
Average of sites less than UII of 25		7	254	46	17	0

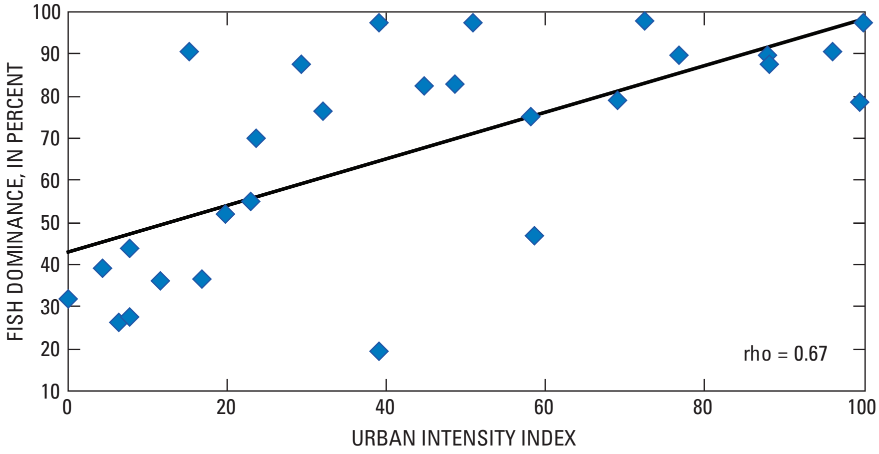


Figure 19. Relation between urban intensity index (UII) and percent dominance by single fish species at all 28 sites (highest relative abundance), Willamette River basin and surrounding area, Oregon and Washington.

Table 16. Correlations of fish metrics and nonmetric dimensional scaling axis 1 ordination scores with environmental variables, Willamette River basin and surrounding area, Oregon and Washington.

[See appendix A for definitions of environmental variables. Correlation coefficients were considered strong when absolute value ≥ 0.66 (bolded and shaded) and moderate when 0.66 > *rho* ≥ 0.50 (bolded). **Abbreviations:** DO, dissolved oxygen; TEQ, toxic equivalent index; SPMD, semipermeable membrane device; TN, total nitrogen; TP, total phosphorus; mg/L, milligram per liter. **Symbols:** >, greater than]

Environmental variables	FISH Index	Percent salmonids	FISH nMDS Axis1
Urban indicator metrics			
Urban intensity index (UII)	**-0.68**	**0.62**	**-0.76**
Percent impervious surface	**-.63**	**.57**	**-.69**
POPDEN00	**-.68**	**.63**	**-.75**
Percent urban + agriculture	**-.56**	.49	**-.68**
ROADDEN	**-.57**	**.54**	**-.69**
Hydrologic variation metrics			
Number of falling events > 5×median (PeriodF5)	**-0.55**	**0.56**	**-0.72**
Number of falling events > 9×median (PeriodF9)	**-.62**	**.53**	**-.63**
Number of rising events > 5×median (PeriodR5)	-.48	.48	**-.66**
Richards-Baker Flashiness Index (Rb-flash)	**-.53**	**.53**	**-.58**
Habitat metrics			
Mean embeddedness (riffle and runs)	**-0.64**	**0.58**	-0.49
Mean width/depth ratio (riffle and runs)	**.61**	**-.53**	.37
Percent riffle habitat	**.63**	**-.78**	**.67**
Mean habitat heterogeneity	**-.50**	**.53**	**-.53**
Water temperature metrics			
Seven day average temperature	-0.15	0.26	**-0.52**
Minimum temperature (95th percentile)	**-.50**	**.60**	**-.67**
Water-chemistry variables			
Summer dissolved oxygen (mg/L)	**0.70**	**-0.81**	**0.77**
Dissolved organic carbon	**-.68**	**.66**	**-.74**
Specific conductance	**-.74**	**.60**	**-.53**
Sulfate concentration	**-.69**	.48	**-.50**
Sum of total insecticides (TN)	**-.59**	.46	**-.69**
Sum of total pesticides (TP)	**-.52**	.43	**-.70**
TEQ (SPMD)	**-.69**	**.70**	**.74**

Multivariate Analysis of Fish Assemblages

Bioindicators, such as ordination axis scores and individual metrics, were correlated against individual environmental variables to gain insight into what was structuring or potentially affecting the fish assemblages. The full fish assemblage, as represented by the scores of the first nMDS ordination axis, was negatively correlated to the UII with no apparent threshold (rho = -0.76; fig. 20*A*). With the exception of the percentage of salmonids metric (which had some high rho correlation values; table 16), the nMDS ordination axes scores had stronger correlations to the environmental variables than the fish index or individual metrics.

The relations between the ordination axis 1 scores and summer DO, TEQ, and PeriodF5 are shown in figures 20*B–D*. A strong linear response was noted in the fish assemblages along the UII and in response to DO concentrations. The response in the TEQ, however, may indicate a potential threshold between 300 and 500 picograms TEQ (fig. 20*B*). The axis 1 ordination scores also were strongly related to three hydrology variation metrics (PeriodF5; fig. 20*D*), percent riffle, minimum temperature, DOC, and sum of insecticides and pesticides (table 16). The BEST routine in PRIMER indicated that summer DO, percent riffles and PeriodF5 could explain about 60 percent of the variation in full fish assemblage data among the sites. The percentage of salmonids compared to the summer DO concentration may also be indicative of a possible threshold response (fig. 21). No salmonids were sampled at sites with midday summer DO concentrations less than 8 mg/L, except at Curtin Creek. Because salmonids require cool waters with high DO to thrive, few were observed during the summer in these Willamette Valley ecoregion streams that often can have high summer temperatures with low dissolved oxygen. The Oregon Department of Environmental Quality standard for DO is 5.5 mg/L and 18 degrees Celsius (7-day moving average for the minimum summer water temperature). Curtin Creek was a unique site and although little high-quality fish habitat was within the sampled reach, it offered salmonids cold clear water during the summer with abundant instream habitat cover in the form of macrophytes and overhanging riparian vegetation. As a result, salmonids probably immigrated from nearby streams into Curtin Creek to take advantage of the cold water during summer.

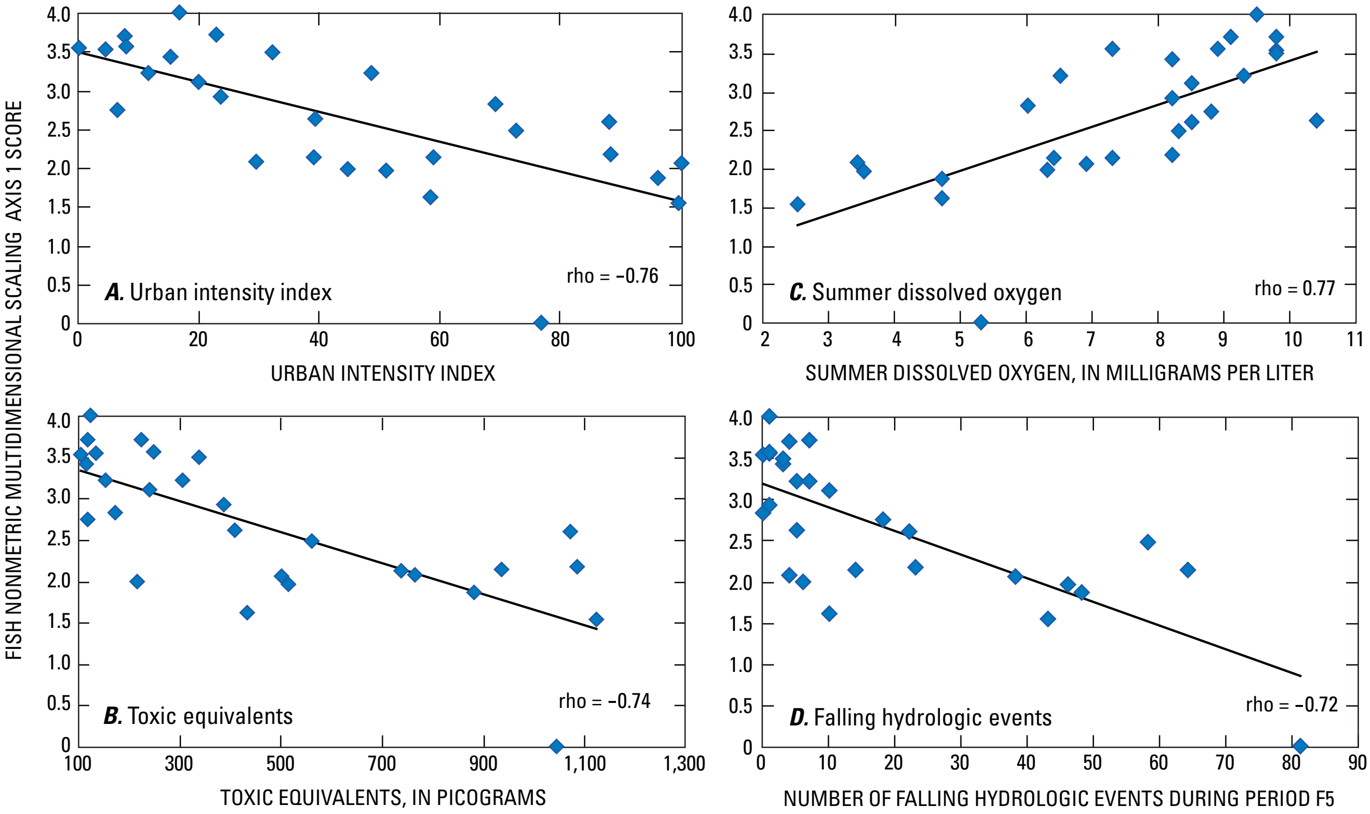


Figure 20. Relation between fish assemblages (nonmetric dimensional scaling first axis ordination scores) and (*A*) urban intensity index (UII), (*B*) toxic equivalents (TEQ) from semipermeable membrane devices, (*C*) summer dissolved oxygen (DO) concentrations and (*D*) the number of falling hydrologic events (PeriodF5), Willamette River basin and surrounding area, Oregon and Washington.

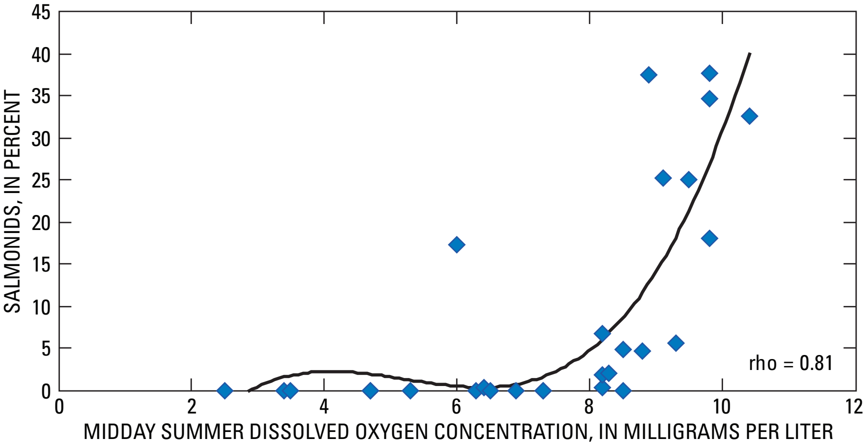


Figure 21. Relation between midday summer dissolved oxygen (DO) concentrations and percentage of salmonids, Willamette River basin and surrounding area, Oregon and Washington.

Summary

This study examined how urbanization affects stream ecosystems. Objectives of the study included an examination of physical, chemical, and biological responses to urbanization of small streams in the Willamette River basin and surrounding area, Oregon and Washington.

Hydrologic variable findings indicate that as urban intensity indicators increased (urban intensity index (UII), road density, percentage of impervious surface and population density), so did the stream flashiness. For example, the response of stream flashiness metrics to urbanization was moderate (0.66 > rho ≥ 0.50) to strong (rho ≥ 0.66) among the sites examined in this study. In addition, as urban indicators increased, minimum water temperature (95th percentile) also increased by a moderate response (0.56 ≥ rho ≥ 0.44). Other moderate responses to increased urbanization included an increase in average substrate embeddedness (riffles and runs), a decrease in average width-to-depth ratio (riffles and runs), and a decrease in the percentage of riffle habitat.

Physical data collected indicated that one of the strongest relations was detected between percentage of riffle habitat and summer dissolved oxygen concentrations (rho = 0.84). It was also discovered that there was a moderate to strong negative correlation of dissolved oxygen with minimum temperature, average substrate embeddedness, and mean habitat heterogeneity (measure of instream habitat diversity). There were other connections between physical and water chemistry, such as, streamflow flashiness metrics showed strong responses to select water-chemistry parameters, including dissolved organic carbon, sum of total pesticides, toxic equivalents (measure of water column contaminants obtained from semipermeable membrane devices), and sulfate concentration. Conversely, streamflow flashiness had a low correlation to nutrients, such as total nitrogen concentration (rho = 0.30).

Most water-chemistry metrics, including sum total insecticide, sum total pesticide, pesticide toxicity index, toxic equivalents (TEQ), and Pyrene index, responded moderately to strongly to each increased urban indicator metric (0.83 ≥ rho ≥ 0.56). For example, the sum of total insecticides correlated strongly to road density, population density, and the urban intensity index (rho = 0.73, 0.70, and 0.69, respectively). However, insecticides were slightly less correlated to percentage of impervious surface and urban plus agricultural land use (rho = 0.66 and 0.63, respectively). Sum of total pesticides was strongly related to each urban metric (rho ≥ 0.66), except percentage of impervious surface where it was moderate (rho = 0.65). The semipermeable membrane device assays correlated positively to urban indictors as well, with toxic equivalents strongly associated to all urban indicator metrics (0.81 ≥ rho ≥ 0.73). The Pyrene index increased moderately to strongly with the increasing urban metrics (0.67 ≥ rho ≥ 0.51). Total nitrogen and total phosphorus both correlated strongly to the urban intensity index (rho = 0.79 and 0.71, respectively). Total nitrogen also correlated positively with the percentage of urban plus agricultural land use. Other water-chemistry metrics with strong correlations that increased with increasing urbanization were specific conductance and dissolved sulfate, whereas dissolved organic carbon, alkalinity, chloride, and summer dissolved oxygen were moderately correlated.

Algal assemblages responded to the nutrient and organic enrichment effects of urbanization (and agriculture at some sites), which included the development of nuisance green algae growths in some streams. For example, blue-green and red algae dominated the relative density in all but one stream, Deep Creek. High-nutrient indicator diatoms and other algal assemblages that tolerate moderate to high degrees of organic enrichment were positively correlated with the urban intensity index (rho = 0.52).

Benthic algal chlorophyll-*a* was highly variable along the urban gradient, but the ash-free dry mass (measure of algal biomass used to indicate the degree of organic enrichment) was positively correlated with the urban intensity index (rho = 0.56). The ash-free dry mass was positively correlated with dissolved organic carbon concentrations, while dissolved oxygen was negatively correlated with dissolved organic carbon concentrations. These findings suggests that nutrient enrichment caused by urbanization increases the organic status of streams by stimulating algal growth and increasing ash-free dry mass. The organic matter eventually decomposes, which leads to the development of tolerant diatoms and heterotrophic algal taxa that make use of energy in the organic compounds. The use of such compounds by bacteria and other heterotrophic organisms consumes dissolved oxygen during respiration into carbon dioxide. Signs that this may be occurring in the more highly urbanized streams include the decrease in the relative abundance of diatom taxa requiring continuously high levels of dissolved oxygen. These sensitive taxa were most abundant at sites with a urban intensity index less than 25, and less abundant at sites higher on the urban gradient. In addition to nutrients and other effects of eutrophication such as organic enrichment, other environmental factors that were determined to be important in shaping the diatom assemblages included various measures of disturbance, such as streamflow flashiness, channel scour, and grazing benthic macroinvertebrates.

Benthic macroinvertebrate assemblages also showed a strong response to urbanization. From the most urbanized sites (urban intensity index greater than 70) to the least urbanized (urban intensity index less than 10), there was an average decrease of 12 Ephemeroptera, Plecoptera and Trichoptera taxa detected. In addition, there was a large increase in percentage of noninsects (31 percent) and percentage of abundance of tolerant taxa (48 percent) between the range of urbanization. At the sites across the full urban gradient, many macroinvertebrate metrics had strong correlations to urban indicators and water-quality variables. For example, Ephemeroptera, Plecoptera and Trichoptera taxa richness (rho = -0.75) and the nMDS ordination axis (rho = -0.83) were highly correlated to the urban intensity index. Macroinvertebrate metrics also had very strong correlations with total pesticide and insecticide concentrations, the pesticide toxicity index, contaminant measures from the semipermeable membrane device samples (TEQ and Pyrene Index), and summer dissolved oxygen. Although all four hydrologic variability and flashiness measures were moderately correlated to macroinvertebrate metrics, they represent less variation than any of the above water-quality variables. Therefore, although flashiness probably was an important issue in the urban areas of the Willamette River basin and surrounding areas, water chemistry issues including contaminants still are a dominant disturbance to macroinvertebrate assemblages followed by flashiness and sedimentation-substrate disturbance or habitat quality.

Fish assemblages showed strong correlation to urbanization, as well. For example, on average, 4 percent salmonids (sensitive) and 8 percent nonnative fish (tolerant) were found at sites with an urban intensity index greater than 25. Conversely, 17 percent salmonids and less than 1 percent nonnative fish were found at sites with an urban intensity index less than 25. All fish metrics, including fish index, salmonid percentage, and ordination axis 1 scores had strong correlations to the urban indicators and water-quality variables and moderate to strong correlation to the hydrologic variability, habitat, and water-temperature measures. Percentage of salmonids and macroinvertebrate Ephemeroptera, Plecoptera and Trichoptera taxa richness indicated a possible threshold response to urbanization at an urban intensity index of 25, which was equivalent to impervious surfaces of about 5 percent. However, due to the added agricultural land use element at sites with urban intensity index values between 25 and 60, this threshold may not be due to urbanization solely, but a combination of urban and agricultural land uses. The effects of agricultural and urban land use could not be distinguished from each other, yet combined provide a good assessment of overall watershed health.

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Appendix A. Variable Definitions

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Table A1. Sources of geographical information system (GIS) and digital data used to derive study basins in the Willamette Valley ecoregion, Oregon and Washington.

Basin characteristics	GIS data theme	Data theme source	Reference or data source
Data used to delineate basins			
Watershed boundaries	National Elevation Dataset (NED)	U.S. Geological Survey	U.S. Geological Survey, 1999, and U.S. Geological Survey Seamless Data Distribution System web site: http://seamless.usgs.gov; data extracted, 2002 and 2003.
	Digital Raster Graphics (DRG)	U.S. Geological Survey and Regional Ecosystem Office	Regional Ecosystem Office (REO) geographical information system (GIS) Data web site: http://www.reo.gov/gis/data/DRG_Files/northwest.asp; data extracted, 2002–05.
	National Hydrography Dataset (NHD)	U.S. Geological Survey	U.S. Geological Survey National Hydrography Dataset web site: http://nhd.usgs.gov/; data extracted 2005.
Data used as geographical information system (GIS) variables			
Demography	Census Blocks and Block Groups 2000, short (SF1) and long forms (SF3)	U.S. Census Bureau	Geolytics Census 2000 Blocks short form CD and Census CD/DVD 2000 long form.
Infrastructure	Census 2000 Topologically Integrated Geographic Encoding and Referencing system (TIGER) Line® files	U.S. Census Bureau	Census TIGER web site: http://www.census.gov/geo/www/tiger/
	National Pollutant Discharge Elimination System (NPDES)	U.S. Environmental Protection Agency	U.S. Environmental Protection Agency Envirofacts web site: http://www.epa.gov/enviro/index_java.html; data extracted, 2002.
	Toxics Release Inventory	U.S. Environmental Protection Agency	U.S. Environmental Protection Agency Envirofacts web site: http://www.epa.gov/enviro/index_java.html; data extracted, 2002.
Land use/land cover, including riparian buffer	National Land Cover Dataset (NLCD) 2001	U.S. Geological Survey	U.S. Geological Survey, 2005; web site: http://www.mrlc.gov/mrlc2k_nlcd.asp; data extracted, 2005.
	National Hydrography Dataset (NHD)	U.S. Geological Survey	U.S. Geological Survey National Hydrography Dataset web site: http://nhd.usgs.gov/; data extracted 2005.
Soil	State Soils Geographic (STATSGO) database	Natural Resources Conservation Service	National Resources Conservation Service web site: http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/; data extracted, 2002.
	Hydrologic soil groups	Natural Resources Conservation Service	National Resources Conservation Service web site: http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/; data extracted, 2002.
Hydrologic landscape regions	Hydrologic landscape regions	U.S. Geological Survey	U.S. Geological Survey web site: http://water.usgs.gov/GIS/metadata/usgswrd/XML/hlrus.xml; data extracted, 2002.
Ecoregion	Ecoregions	U.S. Environmental Protection Agency	U.S. Environmental Protection Agency web site: http://www.epa.gov/wed/pages/ecoregions/level_iii.htm and http://www.epa.gov/wed/pages/ecoregions/level_iv.htm; data extracted, 2002 and 2005; Omernik (1987).
Topography	National Elevation Dataset (NED)	U.S. Geological Survey	U.S. Geological Survey, 1999, and U.S. Geological Survey Seamless Data Distribution System web site: http://seamless.usgs.gov; data extracted, 2002 and 2005.
Climate	Daymet Climatological Summaries for the Conterminous United States, 1980-97	University of Montana, Numerical Terradynamic Simulation Group and National Center for Atmospheric Research (NCAR)	Daymet web site: http://daymet.ntsg.umt.edu/data/data.htm; data extracted, 2005.
FRAGSTATS	National Land Cover Dataset (NLCD) 2001	U.S. Geological Survey and National Oceanic and Atmospheric Administration	McGarigal, Kevin, and Marks, B.J., 1995, FRAGSTATS web site: http://www.umass.edu/landeco/research/fragstats/fragstats.html; data extracted, 2005. Coastal Change and Analysis Program (C-CAP), 2006, web site: http://www.csc.noaa.gov/crs/lca/pacificcoast.html.

Table A2. Variables used to derive the final urban intensity index.

[**Abbreviations:** NLCD, National land cover data; mi, mile; mi^2, square mile]

Variable code	Definition	Spearmans' rho correlation with population density
	Census Variables	
SEI_3	Socioeconomic Index 3: Principal component 3 for 63 socioeconomic variables (2000 census block-group based)	0.92
HHDEN	Household density (occupied housing units per square kilometer) (2000 census block-group based)	.99
PPURBAN	Proportion of population living in urban area (2000 census block-group based)	.92
PP_SH95	Percentage of population living in same house as in 1995 (2000 census block-group based)	-.80
PHUT	Percentage of occupied housing units using utility gas (natural gas) as fuel (2000 census block-group based)	.78
PHLP	Percentage of occupied housing units using liquid petroleum gas as fuel (2000 census block-group based)	-.78
PHWOOD	Percentage of occupied housing units using wood as fuel (2000 census block-group based)	-.90
HUDEN	Density of housing units (housing units per square kilometer) (2000 cesnsus block-group based)	.99
PPRURAL	Proportion of population living in rural area (2000 census block-group based)	-.92
PC_US	Proportion of citizens born in United States (2000 census block-group based)	-.81
PHU_G60	Proportion of housing units built prior to 1939 (2000 census block-group based)	-.73
PPASIA	Proportion of population of Asian ancestry (2000 census block-group based)	.74
	NLCD 2000 Land Cover/Land Use Variables	
pNLCD1_2	Aggregated NLCD 2000 "level 1" category: developed (percentage of basin area)	0.98
pNLCD1_3	Aggregated NLCD 2000 "level 1" category: barren (includes all level 2 barren and unconsolidated categories) (percentage of basin area)	-.79
pNLCD1_4	Aggregated NLCD 2000 "level 1" category: forest (percentage of basin area)	-.91
pNLCD1_5	Aggregated NLCD 2000 "level 1" category: shrubland (includes all level 2 shrub and scrub categories) (percentage of basin area)	-.85
NLCD_IS	NLCD 2000 mean percent impervious surface	.98
	NLCD 2000 Riparian Buffer Variables	
pNLCD1_B2	Buffer area in aggregated NLCD00 "level 1" category: developed (percentage of basin area)	0.97
pNLCD1_B3	Buffer area in aggregated NLCD 2000 "level 1" category: barren (includes all level 2 barren and unconsolidated categories) (percentage of basin area)	-.82
pNLCD1_B4	Buffer area in aggregated NLCD 2000 "level 1" category: forest (percentage of basin area)	-.83
pNLCD1_B5	Buffer area in aggregated NLCD 2000 "level 1" category: shrubland (includes all level 2 shrub and scrub categories) (percentage of basin area)	-.87
NLCD_BIS	NLCD 2000 mean percent impervious surface	.97
	Infrastructure Variables	
ROADDEN	Road density in watershed = [RDLENGTH (mi) / watershed area (mi^2)]	0.95
RDTRINDX	Road traffic index in watershed (weighted miles): road traffic index i = SUM j (length ij * Veh_Traffic_Wt ij) for watershed I and CFCC TIGER code j	.73

Table A3. Watershed variables used in data analysis.

[See table A1 for data sources. **Abbreviations**: m, meter, km^2, square kilometer; cm, centimeter]

Description	Variable code	Definition
Urban intensity index	UII	See text of this report for defintion and full description
Percent impervious surface	NLCD_IS	NLCD 2001 mean percentage of impervious surface within watershed area (based on 30 m resolution data)
POPDEN00	POPDEN00	2000 population density (people per square mile) (2000 census block based)
Percent urban + agriculture	P_NLCD1_2+8	Aggregated P_NLCD 2001 level 1 category: developed (percentage of watershed) + herbaceous planted/cultivated (percentage of watershed)
ROADDEN	ROADDEN	Road density in watershed = (RDLENGTH [kilometers] divided by watershed area [km^2])
Mean watershed elevation	MEANELEV	Mean watershed elevation (m)
Minimum watershed elevation	MIN_ELEV	Minimum watershed elevation (m)
Mean soil erodibility	KFCAVE	Mean soil erodibiity factor (K factor) including rock fragments (unitless)
Percent flat and low elevation land in basin	PFLATLOW	Percentage of watershed area that is flat (slope less than 1 percent) and low (elevation less than midpoint)
Annual precipitation	MAP	Mean annual precipitation (based on 18 years of data) (cm)
Mean percent watershed slope	SLOPE_X	Mean watershed slope (percent)

Table A4. Reach-scale habitat variables.

[**Abbreviations:** mm, millimeter; CV, coefficient of variance. **Symbol:** >, greater than]

Description	Variable code	Definition
Mean embeddedness (riffle and runs)	EmbedPctAvgRR	Mean embeddedness (percent) for transects in riffle and run habitat only (excluding pool)
Mean width/depth ratio (riffle and runs)	WidthDepthAvgRR	Mean wetted-channel width-depth ratio of transects in riffle and run habitat only (excluding pool)
Percent riffle habitat	GCUTypeRiffPct	Relative proportion of the total length of all geomorphic channel units that are comprised of riffles (percent)
Percent large substrate	DomSub5-10Pct	Percentage of occurrence of transect points where the dominant substrate consists of larger than coarse gravel particles (>16 mm)
Mean habitat heterogeneity	stanRHH	sumRHH = Reach Habitat Heterogeneity Index scaled to 0–10, sum of CV of Shape Index, CV velocity, and CV substrate

Table A5. Hydrologic variation metrics.

[**Abbreviations:** POR, period of record. **Symbols:** >, greater than; ≥, greater than or equal to]

Description	Variable code	Definition
Number of falling events > 5×median (PeriodF5)	d_periodf5	Frequency of falling stream-discharge events, where hourly stream-discharge change is ≥5 multiplied by the median fall over POR (number of hourly periods)
Number of falling events > 9×median (PeriodF9)	d_periodf9	Frequency of falling stream-discharge events, where hourly stream-discharge change is ≥9 multiplied by the median fall over POR (number of hourly periods)
Number of rising events > 5×median (PeriodR5)	d_periodr5	Frequency of rising stream-discharge events, where hourly stream-discharge change is ≥5 multiplied by the median rise over POR (number of hourly periods)
Richards-Baker Flashiness Index (Rb-flash)	d_rb_flash	Version of Richards-Baker Flashiness Index (Baker and others, 2004), calculated as the sum of the absolute value of the relative change in daily mean stream discharge, divided by the sum of the daily mean stream discharge for the POR (dimensionless)

Table A6. Stream temperature metrics.

[**Abbreviation:** ODEQ, Oregon Department of Environmental Quality]

Description	Variable code	Definition
Seven day average temperature	7d_Ave_Temp	Maximum of the 7 day moving average water temperature (ODEQ)
Minimum temperature (95th percentile)	t_pct_95n	95th-percentile stream-temperature value over period of record, divided by median stream-temperature value over period of record (dimensionless)

Table A7. Water-chemistry variables.

[**Abbreviations:** DO, dissolved oxygen; N, nitrogen; P, phosphorus; SPMD, semipermeable membrane device; AFDM, ash-free dry mass; TEQ, toxic equivalent; mg/L, milligram per liter; mg/m^2, milligram per square meter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; g/mi^2, gram per square meter]

Description	Variable code	Definition
Instantaneous summer DO (mg/L)	DISSOX	Dissolved oxygen, water, unfiltered (mg/L)
Summer chlorophyll AFDM	NAI	National Water-Quality Assessment Program Autotrophic Index = chlorophyll *a* (mg/m^2) divided by ash-free dry mass (g/m^2)
Average dissolved organic carbon	DISORGC	Organic carbon, water, filtered (mg/L) average of spring and summer samplings
Specific conductance	SPCOND	Specific conductance, water, unfiltered (µS/cm)
Average total suspended sediment	SUSSED	Suspended sediment concentration (mg/L) average of spring and summer samplings
Average sulfate concentration	SULFA	Sulfate, water, filtered (mg/L) average of spring and summer samplings
Average total nitrogen	TOTALN	Total nitrogen, water, unfiltered (mg/L as N) average of spring and summer samplings
Average total phosphorus	TOTALP	Phosphorus, water, unfiltered (mg/L as P) average of spring and summer samplings
Total insecticides (spring + summer)	NUMI	Number of insecticides detected summed for spring and summer samplings
Total pesticides (spring + summer)	NUMP	Number of pesticides detected summed for spring and summer samplings
Pesticide Toxicity Index (spring + summer)	PTIINV	Pesticide Toxicity Index for benthic invertebrates summed for spring and summer samplings
TEQ (SPMD)	SPMDTEQ	SPMD toxicity, CYP1A1 production (toxic equivalents)
Pyrene Index (SPMD)	SPMDUV	SPMD toxicity, ultraviolet fluourescence (micrograms pyrene)

Table A8. Invertebrate variables.

[**Abbreviations:** EPT, ephemeroptera, plecoptera, trichoptera (mayflies, stonefiles, caddisflies); EPEM, Ephemeropera; USEPA, U.S. Environmental Protection Agency; PLECO, Plecoptera; nMDS, non-metric dimensional scaling an ordination technique]

Description	Variable code	Definition
EPEM abundance	EPEM	Abundance of mayflies
EPEM richness	EPEMR	Richness composed of mayflies
EPT/chironomid ratio	EPT_CHR	Ratio of EPT richness to midge richness
EPT richness	EPTR	Richness composed of mayflies, stoneflies, and caddisflies
PLECO percent	PLECOp	Percentage of total abundance composed of stoneflies
PLECO richness	PLECOR	Richness composed of stoneflies
Other diptera percent richness	ODIPNIRp	Percentage of total richness composed of non-midge Diptera and non-insects
Intolerant abundance	Intol_abund	Abundance-weighted USEPA tolerance value for intolerant taxa
Tolerant richness	RICHTOL	Average USEPA tolerance values for sample based on richness
Tolerant percent richness	RICHTOLp	Average USEPA tolerance values for sample based on percent richness
Tolerant abundance	ABUNDTOL	Abundence-weighted USEPA tolerance value for sample
Amphipod percent	AMPHIp	Percentage of total abundance composed of Amphipoda
Noninsect percent richness	NONINSRp	Percentage of total richness composed of noninsects
Oligochaet percent richness	OLOGORp	Percentage of total richness composed of Oligochaeta
nMDS Axis1 score	nMDS axis 1	Axis 1 values from a bi-plot of 2-dimensional distribution based on multivariate similarities

Table A9. List of algal taxa identified in Richest Target Habitat samples, Willamette River basin and surrounding area, Oregon and Washington.

[Algal taxa from 28 Richest Targeted Habitat (RTH) samples. **Abbreviations:** cm^2, square centimeter; µm^3/cm^2, cubic micron per square centimeter; sp., species; var., variety; D, diatom; BG, blue-green algae; G, green algae; E, euglenophyte; R, red algae; aff., affinis (similar to); cf., confer (compare with)]

Scientific name	Algal division	Number of sites	Maximum abundance	
			Density (number of cells/cm^2)	Biovolume (µm^3/cm^2)
Achnanthes conspicua	D	9	174,558	9,316,189
Achnanthes lanceolata var. *haynaldii*	D	8	7,178	2,078,098
Achnanthes ricula	D	2	1,196	1,786,041
Achnanthes sp. 1	D	2	5,692	400,668
Achnanthes subhudsonis var. *kraeuselii*	D	17	1,714,946	87,217,271
Achnanthidium exiguum var. *heterovalvum*	D	2	1,276	142,871
Achnanthidium minutissimum	D	27	731,894	29,102,105
Achnanthidium pyrenaicum	D	2	805	66,995
Achnanthidium sp. 10	D	18	526,964	44,451,564
Adlafia bryophila	D	4	22,770	1,077,659
Adlafia sp. 2	D	1	1,196	136,376
Amphora copulata	D	4	1,196	2,109,603
Amphora inariensis	D	3	89,606	16,001,306
Amphora pediculus	D	13	352,026	35,385,789
Anorthoneis excentrica	D	1	66	497,890
Aphanocapsa sp.	BG	1	3,776,737	94,418,425
Asterionella formosa	D	3	598	247,697
Aulacoseira ambigua	D	2	2,951	1,058,304
Aulacoseira crenulata	D	7	58,114	34,735,559
Aulacoseira distans	D	1	360	127,017
Aulacoseira granulata	D	5	31,906	15,312,909
Aulacoseira italica	D	1	360	298,628
Aulacoseira muzzanensis	D	1	719	2,292,481
Bacillaria paradoxa	D	5	33,602	39,311,265
Caloneis amphisbaena	D	1	360	2,919,321
Caloneis bacillum	D	4	8,374	3,757,193
Caloneis hyalina	D	8	8,401	2,974,192
Caloneis schumanniana	D	1	719	583,193
Caloneis silicula	D	2	268	368,071
Calothrix fusca	BG	1	48,528	12,433,455
Cladophora glomerata	G	2	50,004	51,340,971,926
Cocconeis pediculus	D	1	58	202,379
Cocconeis placentula	D	1	2,517	1,861,795
Cocconeis placentula var. *euglypta*	D	25	164,655	130,032,466
Cocconeis placentula var. *lineata*	D	18	121,015	130,040,130
Cocconeis placentula var. *pseudolineata*	D	1	215	381,612
Ctenophora pulchella var. *lacerata*	D	2	700	6,031,252
Cyclostephanos tholiformis	D	3	15,953	3,094,622
Cyclotella meneghiniana	D	4	28,002	23,428,779
Cyclotella pseudostelligera	D	2	2,551	217,556
Cyclotella stelligera	D	1	268	65,023
Cymbella cymbiformis	D	1	1,290	2,664,683
Cymbella mesiana	D	2	9,686	20,770,780
Cymbella mexicana	D	2	4,879	217,210,927
Cymbella sp. 1	D	1	2,198	4,075,979
Cymbella tumida	D	1	5,692	16,095,195
Denticula tenuis	D	1	598	303,256
Diadesmis confervacea	D	3	78,406	27,045,903
Diadesmis contenta	D	3	9,686	340,549
Diatoma vulgaris	D	2	95,718	286,082,017
Diploneis elliptica	D	2	334	622,325
Diploneis parma	D	2	8,728	12,167,326
Diploneis pseudovalis	D	1	360	308,851
Encyonema minutum	D	7	108,157	22,377,969
Encyonema prostratum	D	1	15,953	29,576,818
Encyonema silesiacum	D	11	267,546	91,228,617
Eunotia exigua	D	4	1,543	258,799
Eunotia flexuosa	D	3	4,843	14,241,971
Eunotia formica	D	1	37	283,292
Eunotia incisa	D	1	805	299,498
Eunotia minor	D	6	24,510	12,949,517
Eunotia monodon	D	1	719	1,575,396
Eunotia muscicola var. *tridentula*	D	1	268	150,230
Eunotia pectinalis var. *undulata*	D	1	9,686	28,244,330
Eunotia pirla	D	1	5,692	18,099,135
Eunotia praerupta	D	1	134	462,764
Fallacia tenera	D	1	1,196	8,973,273
Fragilaria capucina var. *gracilis*	D	6	45,540	3,312,529
Fragilaria capucina var. *rumpens*	D	3	360	40,537
Fragilaria cf. *crotonensis*	D	4	63,431	54,360,226
Fragilaria crotonensis	D	1	117	49,676
Fragilaria nanana	D	1	58	6,056
Fragilaria sp. 7	D	2	15,953	5,341,112
Fragilaria vaucheriae	D	7	23,929	5,149,988
Fragilariforma bicapitata	D	1	4,843	4,150,282
Fragilariforma virescens	D	1	37	31,945
Frustulia amphipleuroides	D	1	4,879	27,566,671
Frustulia crassinervia	D	1	537	230,454
Frustulia rhomboides	D	1	37	131,964
Frustulia vulgaris	D	6	24,510	21,310,568
Frustulia weinholdii	D	1	9,804	27,001,994
Geissleria acceptata	D	3	5,819	4,579,240
Gomphoneis eriense var. *variabilis*	D	1	20,585	628,550,203
Gomphoneis herculeana	D	1	430	2,884,920
Gomphoneis minuta	D	1	9,501	290,100,101
Gomphonema aff. *Kobayasii*	D	19	222,006	1,585,057
Gomphonema affine	D	5	22,770	28,562,881
Gomphonema americobtusatum	D	3	334	435,107
Gomphonema angustatum	D	11	24,396	7,340,544

Table A9. List of algal taxa identified in Richest Target Habitat samples, Willamette River basin and surrounding area, Oregon and Washington.—Continued

[Algal taxa from 28 Richest Targeted Habitat (RTH) samples. **Abbreviations:** cm^2, square centimeter; $\mu m^3/cm^2$, cubic micron per square centimeter; sp., species; var., variety; D, diatom; BG, blue-green algae; G, green algae; E, euglenophyte; R, red algae; aff., affinis (similar to); cf., confer (compare with)]

Scientific name	Algal division	Number of sites	Maximum abundance	
			Density (number of cells/cm^2)	Biovolume ($\mu m^3/cm^2$)
Gomphonema bipunctatum	D	1	360	468,093
Gomphonema drutelingense	D	1	1,609	2,095,005
Gomphonema gracile	D	4	15,953	16,744,119
Gomphonema innocens	D	3	56,925	32,754,489
Gomphonema kobayasii	D	21	251,015	36,550,747
Gomphonema lagenula	D	13	23,929	6,231,043
Gomphonema mexicanum	D	2	2,682	2,889,033
Gomphonema micropus	D	3	4,902	1,445,550
Gomphonema minutum	D	3	2,909	509,968
Gomphonema parvulius	D	1	5,600	7,291,720
Gomphonema parvulum	D	5	31,906	7,953,419
Gomphonema parvulum var. *saprophilum*	D	1	719	936,186
Gomphonema patrickii	D	1	537	143,654
Gomphonema pumilum	D	1	2,683	598,872
Gomphonema rhombicum	D	17	136,619	62,448,261
Gomphonema sp. 2	D	4	775,808	282,880,603
Gomphonema sp. 3	D	1	37	48,533
Gomphonema subclavatum	D	1	360	239,466
Gomphosphenia lingulatiformis	D	1	22,729	10,921,783
Gyrosigma acuminatum	D	1	202	1,418,469
Gyrosigma nodiferum	D	1	4,843	18,880,003
Gyrosigma scalproides	D	1	2,451	3,591,376
Hantzschia amphioxys	D	3	598	664,160
Heteroleibleinia sp.	BG	1	251,348	2,149,644
Hippodonta capitata	D	4	9,804	3,297,494
Homoeothrix janthina	BG	21	11,854,144	43,235,144
Homoeothrix juliana	BG	4	979,535	51,670,281
Karayevia clevei	D	2	360	58,612
Karayevia laterostrata	D	1	771	1,151,596
Leptolyngbya sp.	BG	9	9,510,686	30,054,496
Luticola goeppertiana	D	1	16,801	12,950,671
Luticola mutica	D	2	719	421,950
Mayamaea atomus	D	2	15,953	514,641
Melosira varians	D	16	250,469	1,231,832,428
Meridion circulare var. *constrictum*	D	4	5,600	1,492,472
Merismopedia glauca	BG	1	643,866	12,034,106
Navicula absoluta	D	1	4,187	998,760
Navicula antonii	D	9	31,906	4,776,375
Navicula arvensis	D	1	719	43,775
Navicula capitatoradiata	D	2	1,196	672,127
Navicula concentrica	D	8	55,835	34,511,814
Navicula constans var. *symmetrica*	D	1	360	386,180
Navicula cryptocephala	D	10	34,314	11,320,621
Navicula cryptotenella	D	17	68,310	16,471,200
Navicula germainii	D	4	39,203	17,499,767
Navicula gregaria	D	11	12,255	3,225,920
Navicula hintzii	D	1	5,981	1,733,616
Navicula ingenua	D	2	2,991	129,566
Navicula integra	D	1	3,015	1,241,277
Navicula kotschyi	D	1	268	62,799
Navicula lanceolata	D	10	15,953	23,134,226
Navicula menisculus	D	4	1,414	534,228
Navicula minima	D	21	313,086	12,682,552
Navicula mobiliensis var. *minor*	D	1	7,353	15,569,915
Navicula peregrina	D	1	101	346,236
Navicula pseudotenelloides	D	1	22,402	1,201,442
Navicula radiosa	D	1	37	41,391
Navicula recens	D	1	1,543	777,048
Navicula reichardtiana	D	1	1,720	207,842
Navicula reinhardtii	D	1	112	297,952
Navicula rhynchocephala	D	1	771	551,936
Navicula rostellata	D	3	11,201	8,958,057
Navicula ruttnerii var. *capitata*	D	2	7,178	640,216
Navicula schroeteri var. *escambia*	D	12	66,177	48,109,997
Navicula sp. 44	D	1	3,167	3,042,572
Navicula sp. 47	D	1	6,334	334,297
Navicula subadnata	D	1	133	995,781
Navicula subminuscula	D	3	31,906	2,050,933
Navicula tenelloides	D	6	9,686	1,218,147
Navicula tripunctata	D	7	9,316	8,675,142
Navicula trivialis	D	4	5,393	3,898,691
Navicula veneta	D	2	1,196	200,083
Navicula viridulacalcis	D	2	1,794	13,459,929
Navicula wallacei	D	1	268	97,606
Nitzschia acidoclinata	D	2	489	5,728,823
Nitzschia agnita	D	1	15,953	1,459,116
Nitzschia amphibia	D	18	624,722	121,686,962
Nitzschia angustata	D	1	1,196	6,291,970
Nitzschia archibaldii	D	1	15,953	997,034
Nitzschia brevissima	D	1	805	337,018
Nitzschia capitellata	D	5	9,804	3,673,000
Nitzschia dissipata	D	17	239,295	59,895,837
Nitzschia filiformis	D	1	2,800	2,172,325
Nitzschia fonticola	D	16	199,412	18,979,964
Nitzschia fossilis	D	1	2,393	28,026,405
Nitzschia gracilis	D	2	1,196	432,220
Nitzschia heufleriana	D	5	2,991	14,712,836
Nitzschia inconspicua	D	17	311,083	9,212,723
Nitzschia intermedia	D	2	1,196	828,511
Nitzschia liebethruthii	D	1	1,276	114,439
Nitzschia linearis	D	3	17,456	47,656,820
Nitzschia linearis var. *subtilis*	D	3	2,451	1,941,599
Nitzschia palea	D	10	12,255	3,233,473
Nitzschia palea var. *debilis*	D	6	19,517	2,887,687
Nitzschia perminuta	D	1	101	9,803

Table A9. List of algal taxa identified in Richest Target Habitat samples, Willamette River basin and surrounding area, Oregon and Washington.—Continued

[Algal taxa from 28 Richest Targeted Habitat (RTH) samples. **Abbreviations:** cm^2, square centimeter; $\mu m^3/cm^2$, cubic micron per square centimeter; sp., species; var., variety; D, diatom; BG, blue-green algae; G, green algae; E, euglenophyte; R, red algae; aff., affinis (similar to); cf., confer (compare with)]

Scientific name	Algal division	Number of sites	Maximum abundance	
			Density (number of cells/cm^2)	Biovolume ($\mu m^3/cm^2$)
Nitzschia radicula	D	1	9,686	113,457,180
Nitzschia recta	D	7	15,953	28,511,891
Nitzschia sigmoidea	D	13	24,214	64,554,667
Nitzschia sociabilis	D	6	39,216	8,558,069
Nitzschia solita	D	1	5,600	1,066,901
Nitzschia tubicola	D	1	1,276	288,948
Nitzschia vermicularis	D	1	11,201	51,243,212
Nupela silvahercynia	D	2	16,198	121,500,890
Nupela sp. 1	D	3	202,089	2,241,256
Nupela wellneri	D	1	1,196	8,973,273
Oedogonium sp.	G	6	56,756	1,132,047,129
Oscillatoria princeps	BG	1	4,897,853	358,250,872
Pandorina morum	G	1	32,885	2,795,192
Parlibellus protracta	D	1	37	33,772
Phormidium autumnale	BG	16	4,011,385	188,628,500
Phormidium retzii	BG	3	150,011	22,207,813
Pinnularia divergens	D	4	207	1,552,878
Pinnularia microstauron	D	4	4,902	5,905,940
Pinnularia sudetica	D	1	638	2,370,394
Pinnularia viridis	D	1	1,079	5,906,620
Placoneis elginensis	D	1	1,438	759,305
Planothidium delicatulum	D	1	1,196	368,248
Planothidium frequentissimum	D	20	86,806	6,694,362
Planothidium lanceolatum	D	22	215,365	53,446,394
Planothidium rostratum	D	7	4,843	576,598
Porphyrosiphon luteus	BG	1	1,029,009	25,725,232
Porphyrosiphon martensianus	BG	6	3,316,956	357,276,740
Psammothidium lauenburgianum	D	1	5,819	8,687,172
Pseudanabaena sp.	BG	8	533,669	1,387,073
Reimeria sinuata	D	18	91,080	15,338,294
Rhoicosphenia abbreviata	D	25	726,420	307,435,607
Rhopalodia gibba	D	1	1,196	7,244,122
Scenedesmus acutus	G	1	13,354	432,707
Scenedesmus denticulatus	G	1	49,219	1,000,115
Scenedesmus ecornis	G	2	30,002	744,477
Scenedesmus quadricauda	G	2	30,002	988,363
Sellaphora laevissima	D	2	805	895,327
Sellaphora pupula	D	8	16,801	7,770,995
Sellaphora seminulum	D	21	143,577	486,913,494
Simonsenia delognei	D	4	8,728	456,124
Spirogyra sp.	G	1	10,016	808,152,137
Stauroneis kriegeri	D	4	805	124,252
Stauroneis phoenicenteron	D	1	207	11,516,940
Staurosira construens	D	2	11,385	2,379,854
Staurosira construens var. *binodis*	D	2	137,210	68,470,231
Staurosira construens var. *subsalina*	D	1	11,201	3,170,875
Staurosira construens var. *venter*	D	4	106,542	9,569,688
Staurosira elliptica	D	1	117	5,501
Staurosirella pinnata	D	1	62,956	10,134,217
Stephanodiscus hantzschii	D	1	360	115,171
Stephanodiscus minutulus	D	1	202	58,697
Stigeoclonium lubricum	G	1	213,468	84,043,977
Surirella amphioxys	D	1	360	384,625,288
Surirella angusta	D	6	5,600	6,141,920
Surirella biseriata	D	2	5,600	89,695,680
Surirella brebissonii var. *kuetzingii*	D	4	11,637	11,901,456
Synedra acus	D	2	2,909	4,921,361
Synedra parasitica	D	6	52,367	4,721,265
Synedra parasitica var. *subconstricta*	D	2	1,276	126,279
Synedra ulna	D	16	22,402	124,196,962
Tabellaria flocculosa	D	1	268	121,629
Thalassiosira pseudonana	D	3	15,953	763,341
Trachelomonas volvocina	E	2	5,930	8,715,732
Tryblionella apiculata	D	2	5,600	2,114,415
Tryblionella calida	D	2	5,600	6,062,124
Tryblionella debilis	D	1	4,902	1,807,780
Tryblionella victoriae	D	1	268	3,142,500
Unknown Cyanophyte (colonial coccoid)	BG	8	113,512	143,431,520
Unknown Cyanophyte (colonial coccoid)	BG	1	6,180,652	2,697,679,030
Unknown Rhodophyte Florideophycidae (chantransia)	R	25	2,442,559	1,174,999,542

Table A10. Macroinvertebrate species list sorted alphabetically by scientific name, order, number of sites collected (richest target habitat samples) and maxmum abundance among all 28 sites, Willamette River basin and surrounding area, Oregon and Washington.

[**Abbreviation:** sp., species]

Scientific name	Order	Number of sites	Maximum abundance
Ablabesmyia sp.	Diptera	1	41
Acari	Phylum Arthopoda	27	988
Acentrella turbida	Ephemeroptera	8	1,455
Ampumixis dispar	Coleoptera	1	54
Anisogammarus sp.	Amphipoda	4	536
Anopheles sp.	Diptera	1	20
Antocha sp.	Diptera	4	141
Arctopsyche grandis	Trichoptera	1	1
Argia sp.	Odonata	5	90
Atherix pachypus	Diptera	1	16
Baetis tricaudatus	Ephemeroptera	23	3,082
Brillia sp.	Diptera	11	86
Bryozoa	Phylum	1	6
Caecidotea sp.	Isopoda	8	877
Caenis sp.	Ephemeroptera	1	64
Calineuria californica	Plecoptera	11	228
Capniidae	Plecoptera	1	31
Cardiocladius sp.	Diptera	2	260
Ceratopogonidae	Diptera	1	54
Ceratopsyche cockerelli	Trichoptera	14	2,904
Chelifera/Metachela sp.	Diptera	3	141
Cheumatopsyche sp.	Trichoptera	19	3,467
Chironomus sp.	Diptera	1	64
Cleptelmis addenda	Coleoptera	5	323
Collembola	Collembola	2	32
Corbicula sp.	Veneroida	3	282
Corynoneura sp.	Diptera	4	30
Crangonyx sp.	Amphipoda	15	661
Cricotopus bicinctus group	Diptera	16	3,303
Cryptochironomus sp.	Diptera	2	64
Cryptotendipes sp.	Diptera	1	31
Culex sp.	Diptera	1	64
Curculionidae	Coleoptera	1	16
Dero sp.	Tubificida	22	2,123
Dicosmoecus gilvipes	Trichoptera	5	57
Dicranota sp.	Diptera	2	27
Dicrotendipes sp.	Diptera	3	153
Diphetor hageni	Ephemeroptera	6	56
Diplocladius cultriger	Diptera	2	387
Dixa sp.	Diptera	1	32
Drunella doddsi	Ephemeroptera	4	257
Drunella grandis	Ephemeroptera	1	65
Enchytraeidae	Enchytraeida	2	371
Epeorus sp.	Ephemeroptera	1	556
Ephemerella sp.	Ephemeroptera	1	23
Eukiefferiella sp.	Diptera	16	864
Eukiefferiella/Tvetenia sp.	Diptera	1	23
Ferrissia sp.	Basommatophora	16	790
Fluminicola sp.	Mesogastropoda	15	11,419
Glossosoma sp.	Trichoptera	5	484
Glyptotendipes sp.	Diptera	1	64
Gomphidae	Odonata	2	113
Hemerodromia sp.	Diptera	7	80
Hesperoperla pacifica	Plecoptera	9	94
Heterlimnius sp.	Coleoptera	1	17
Hexatoma sp.	Diptera	1	32
Hyalella azteca	Amphipoda	2	1,401
Hydra sp.	Hydroida	1	32
Hydropsyche sp.	Trichoptera	2	211
Hydroptila sp.	Trichoptera	3	61
Ironodes sp.	Ephemeroptera	4	145
Juga sp.	Mesogastropoda	25	3,870
Lara sp.	Coleoptera	9	147
Lepidoptera	Lepidoptera	1	64
Lepidostoma sp.	Trichoptera	5	78
Leptohyphidae	Ephemeroptera	1	97
Leucotrichia pictipes	Trichoptera	1	269
Limnophyes sp.	Diptera	4	121
Lumbriculidae	Lumbriculida	20	581
Malenka sp.	Plecoptera	6	134
Margaritifera falcata	Paleoheterodonta	4	2
Megadrile	Class Oligochaeta	12	194
Menetus sp.	Basommatophora	5	107
Micrasema sp.	Trichoptera	4	134
Micropsectra sp.	Diptera	8	311
Micropsectra/Tanytarsus sp.	Diptera	13	933
Microtendipes sp.	Diptera	2	15
Nanocladius sp.	Diptera	3	27
Narpus sp.	Coleoptera	4	81
Nematoda	Phylum	12	107
Nematomorpha	Phylum	1	1
Neophylax sp.	Trichoptera	2	2
Neoplasta sp.	Diptera	2	80
Onocosmoecus sp.	Trichoptera	1	1
Optioservus sp.	Coleoptera	16	1,349
Ordobrevia nubifera	Coleoptera	2	97
Pacifastacus leniusculus	Decapoda	15	20
Parakiefferiella sp.	Diptera	1	11
Paraleptophlebia sp.	Ephemeroptera	19	672
Paramerina sp.	Diptera	2	22
Parametriocnemus sp.	Diptera	13	671
Paraphaenocladius sp.	Diptera	1	13
Paratanytarsus sp.	Diptera	9	541
Pericoma/Telmatoscopus sp.	Diptera	1	27
Perlinodes aureus	Plecoptera	1	270
Phaenopsectra sp.	Diptera	5	130
Physa sp.	Basommatophora	5	82
Pisidium sp.	Veneroida	12	222
Polypedilum sp.	Diptera	19	307
Porifera	Phylum	1	6
Prostoma sp.	Hoplonemertea	9	40
Psephenus falli	Coleoptera	1	1,322

Table A10. Macroinvertebrate species list sorted alphabetically by scientific name, order, number of sites collected (richest target habitat samples) and maximum abundance among all 28 sites, Willamette River basin and surrounding area, Oregon and Washington.—Continued

[**Abbreviation:** sp., species]

Scientific name	Order	Number of sites	Maximum abundance
Pseudocloeon sp.	Ephemeroptera	1	80
Psychomyia sp.	Trichoptera	1	16
Pteronarcella sp.	Plecoptera	1	27
Pteronarcys californica	Plecoptera	4	33
Rheocricotopus sp.	Diptera	5	32
Rheotanytarsus sp.	Diptera	16	1,050
Rhithrogena sp.	Ephemeroptera	15	3,057
Rhyacophila betteni group	Trichoptera	12	323
Rhyacophila hyalinata group	Trichoptera	1	188
Rhyacophila sibirica group	Trichoptera	1	105
Rhyacophila vedra	Trichoptera	5	39
Sialis sp.	Megaloptera	5	40
Simulium arcticum complex	Diptera	1	776
Simulium canadense	Diptera	27	12,306
Skwala sp.	Plecoptera	5	215
Sphaerium sp.	Veneroida	1	484
Staphylinidae	Coleoptera	1	16
Stempellinella sp.	Diptera	3	820
Stenochironomus sp.	Diptera	2	23
Sublettea coffmani	Diptera	2	315
Sweltsa sp.	Plecoptera	13	501
Synorthocladius sp.	Diptera	2	15
Tanytarsus sp.	Diptera	7	113
Thienemanniella sp.	Diptera	9	97
Thienemannimyia group	Diptera	17	451
Tipula sp.	Diptera	2	28
Tribelos sp.	Diptera	1	8
Tubificidae	Tubificida	15	2,129
Turbellaria	Class	7	387
Tvetenia sp.	Diptera	6	241
Unionacea	Paleoheterodonta	1	23
Wormaldia gabriella	Trichoptera	4	419
Xenochironomus xenolabis	Diptera	2	64
Zaitzevia parvula	Coleoptera	12	885
Zaitzevia posthonia	Coleoptera	2	101
Zapada cinctipes	Plecoptera	16	4,081

Table A11. Fish species list sorted by Order, Family, and scientific name, fish common name, native or nonnative species, number of sites collected and maximum abundance among all 28 sites, Willamette River basin and surrounding area, Oregon and Washington.

Order	Family	Scientific name	Common name	Native or nonnative	Number of sites	Maximum abundance
Petromyzontiformes	Petromyzontidae	*Lampetra richardsoni*	western brook lamprey	Native	16	4
Petromyzontiformes	Petromyzontidae	*Lampetra tridentata*	Pacific lamprey	Native	2	1
Atheriniformes	Poeciliidae	*Gambusia affinis*	western mosquitofish	Nonnative	2	36
Cypriniformes	Catostomidae	*Catostomus macrocheilus*	largescale sucker	Native	10	13
Cypriniformes	Cyprinidae	*Cyprinus carpio*	common carp	Nonnative	1	8
Cypriniformes	Cyprinidae	*Ptychocheilus oregonensis*	northern squawfish	Native	6	5
Cypriniformes	Cyprinidae	*Rhinichthys cataractae*	longnose dace	Native	6	12
Cypriniformes	Cyprinidae	*Rhinichthys osculus*	speckled dace	Native	20	55
Cypriniformes	Cyprinidae	*Richardsonius balteatus*	redside shiner	Native	18	105
Gasterosteiformes	Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Native	1	1
Perciformes	Centrarchidae	*Ambloplites rupestris*	rock bass	Nonnative	1	1
Perciformes	Centrarchidae	*Lepomis gibbosus*	pumpkinseed	Nonnative	5	6
Perciformes	Centrarchidae	*Lepomis macrochirus*	bluegill	Nonnative	1	42
Perciformes	Centrarchidae	*Micropterus salmoides*	largemouth bass	Nonnative	4	536
Perciformes	Centrarchidae	*Pomoxis annularis*	white crappie	Nonnative	2	2
Percopsiformes	Percopsidae	*Percopsis transmontana*	sand roller	Native	2	4
Salmoniformes	Salmonidae	*Oncorhynchus clarki*	cutthroat trout	Native	14	47
Salmoniformes	Salmonidae	*Oncorhynchus kisutch*	coho salmon	Native	11	96
Salmoniformes	Salmonidae	*Oncorhynchus mykiss*	rainbow trout	Native	9	121
Scorpaeniformes	Cottidae	*Cottus asper*	prickly sculpin	Native	3	9
Scorpaeniformes	Cottidae	*Cottus beldingi*	Paiute sculpin	Native	3	51
Scorpaeniformes	Cottidae	*Cottus perplexus*	reticulate sculpin	Native	28	532
Scorpaeniformes	Cottidae	*Cottus rhotheus*	torrent sculpin	Native	15	157
Siluriformes	Ictaluridae	*Ameiurus melas*	black bullhead	Nonnative	1	1
Siluriformes	Ictaluridae	*Ameiurus natalis*	yellow bullhead	Nonnative	1	2
Siluriformes	Ictaluridae	*Ameiurus nebulosus*	brown bullhead	Nonnative	2	8

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