Watershed Delineation and Land Cover Calculations for Puget Sound Stream Basins

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Abstract

Geographic information system (GIS) procedures and analyses were used to calculate contributing watershed areas and landscape scale metrics for 1,132 benthic macroinvertebrate sampling locations in the Puget Sound basin. Watershed boundaries were calculated using automated methods; a manual quality control review was conducted and data adjusted where deemed in error. Landscape metrics were calculated for land cover (e.g., % urbanization), physical conditions (e.g., elevation, watershed area), and human disturbance (e.g. road density, population density). The delineated watersheds reflected land cover ranging from least to most disturbed conditions. These landscape metrics were used to measure human disturbance, test and refine taxa attributes used to calculate individual metrics for the Benthic Index of Biotic Integrity (B-IBI), and recalibrate the B-IBI. A GIS shape file of the contributing watershed basins and an Excel® flat file of the land use/land cover calculations are available as separate electronic attachments for use by interested Puget Sound region partner agencies.

Introduction

This document describes the geographic information system (GIS) procedures and analyses used to calculate contributing watershed areas and landscape scale metrics for 1,132 benthic macroinvertebrate sampling locations in the Puget Sound basin. The resulting data are a critical part of the Environmental Protection Agency (EPA)-funded project entitled "Enhancement and Standardization of Benthic Macroinvertebrate Monitoring and Analysis Tools for the Puget Sound Region." The land use/land cover data are being used to measure human disturbance, test and refine taxa attributes used to calculate individual metrics for the Benthic Index of Biotic Integrity (B-IBI) (Fore et al. 2012), and recalibrate the B-IBI. A GIS shape file of the contributing watershed basins and an Excel flat file of the land use/land cover calculations are available for download from the Puget Sound Stream Benthos data management system (PSSB[1]) as separate electronic attachments for use by interested Puget Sound region partner agencies.

[1] Documents and data are available for download: http://www.pugetsoundstreambenthos.org/Projects/Improving-Biological-Monitoring-Tools-Documentation.aspx.

Methods

The watershed boundary calculations and landscape sampling methods required multiple steps, including data acquisition and GIS calculations. A summary of these methods are presented here. For additional details regarding the specific methods please refer to the two technical memos prepared by Leinenbach (2011a, b). All GIS analyses and calculations were completed using ArcGIS desktop software obtained from ESRI.

Watershed boundary calculations

Watershed boundaries were calculated by (1) downloading and preparing data, (2) snapping sampling locations to the stream layer, (3) calculating watershed area, (4) checking results, and (5) recalculating the analysis where problems are identified in step 4. Steps 2 and 3 were automated which saved time compared to alternative manual approaches. Each step is described in more detail below.

1. **Data download and preparation.**
    a. Latitude and longitude coordinates for each sampling location were downloaded in decimal degrees from the PSSB[2] and converted to a GIS shapefile with a geographic projection.
    b. The following datasets were downloaded from the National Hydrography Dataset (NHD)[3] using NHDPlus Version 1[4]:
        i. 1:100,000 NHD (2006)
        ii. 30 meter National Elevation Dataset (NED) (2004)
        iii. Flow direction and flow accumulation grids
        iv. Catchment boundaries
    c. Preparation of NHD data files included building attribute and spatial information for shape files, building pyramids for grids to increase processing efficiency[5], and preprocessing the NHDPlus data[6].
2. **Snap sampling locations to the stream layer**. The points in the sampling location shapefile were moved or "snapped" to the nearest location on the NHD digital elevation model (DEM) derived stream layer. A search radius of 0.001 degrees (~ 0.07 miles) worked for most sites; however a search radius of 0.005 degrees (~ 0.35 miles) was necessary for some sampling locations. This step was necessary in order to calculate an accurate watershed area from the NHDPlus datasets.
3. **Calculate watershed area**. Watershed areas were calculated using the "Batch Watershed Delineation" tool in the ArcHydro extension.

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[2] www.pugetsoundstreambenthos.org
[3] www.horizon-systems.com/NHDPlus/NHDPlusV1_17.php
[4] NHDPlusV1 was replaced by NHDPlusV2 in June 2012. Most of our analysis was completed by June 2011, therefore NHDPlusV1 was used.
[5] Tutorial One on the NHDPlusV1 web page describes in detail how to set up spatial information for shape files and grids: ftp://ftp.horizon-systems.com/NHDPlus/NHDPlusV1/exercises/NHDPlus-Exercise1-SettingUpTheData.pdf
[6] Tutorial Seven on the NHDPlusV1 web page describes in detail how to preprocess the NHD data: ftp://ftp.horizon-systems.com/NHDPlus/NHDPlusV1/exercises/NHDPlus-Exercise7-WatershedDelineation.pdf. There is one glitch in the directions: do not save the mxd before adding data into the project (in the section called "Using the preprocessed data for watershed delineation"). It will work if data is first added and then the file is saved.

4. **Check results.** There are three possible errors associated with using the automated methodology to estimate the pour point location:
    a. Snapping to the incorrect stream. This happens when several streams are close to the sampling point. The automated method snaps the point to the closest stream; however, this might not be the desired target stream. Determining this error requires visual inspection of each point and knowledge of the precise sampling location. Despite significant data review, errors of this type may persist in the dataset.
    b. Not snapping to any stream line. This can happen when (1) a sampling location is farther away from any stream than the established sampling radius, (2) there are few or no GIS stream layers in very flat areas, or (3) the GIS location of the point is incorrect. With this type of error the watershed boundary is very small and strangely shaped, making it easy to identify.
    c. Snapping to a stream line, but the line doesn't overlay the grid data. This type of error is also easy to identify because it results in a very small watershed area.
5. **Recalculate problem watersheds, if necessary**.
    a. Inspect watershed area to identify watersheds which have been incorrectly derived (see errors 4b and 4c, Figure 1).
    b. Visually inspect all points to identify watersheds where the pour point may have snapped to the incorrect stream. Topographic maps, aerial photos, and NHD streams layer may be useful in this situation.
    c. Create a new shapefile of the "problem" watersheds and correct the pour point location using automated methods for the small watershed errors or manually for the watersheds that snapped to the incorrect stream.
    d. Repeat step 3 (recalculate watershed area).

Attributes of Waters

Shape *	OID *	Shape_Length	Shape_Area	HydroID	Name
Polygon	24	120	900	239	Potlatch Creek - site 1
Polygon	8	120	900	207	SEABECK
Polygon	21	120	900	233	Big Anderson Creek
Polygon	18	120	900	227	Swift Creek - site 2
Polygon	10	120	900	211	Steele Creek - South Fork
Polygon	20	180	1800	231	Vance Creek - site 2
Polygon	16	240	1800	223	Potlatch Creek - site 2
Polygon	5	180	1800	201	DUCKABU
Polygon	17	360	2700	225	Skokomish River - Site 2
Polygon	23	420	3600	237	Enetai Creek - site 1
Polygon	25	480	3600	241	Purdy Creek - site 2
Polygon	4	300	3600	199	Dickerson Creek
Polygon	7	360	4500	205	Little Boston
Polygon	6	720	13500	203	Little Anderson Creek
Polygon	12	8280	1756799.999999	215	Enetai Creek - site 2
Polygon	15	10800	2807100	221	Olalla Creek
Polygon	13	11100	3182399.999999	217	Harding
Polygon	2	17580	4073399.999999	195	Boyce Creek
Polygon	22	17580	7781400.000002	235	DEWATTO
Polygon	9	25500	8564400.000001	209	Stavis Creek
Polygon	14	30780	15303600.000001	219	LITTLEA
Polygon	11	26880	16187400.000002	213	Burley Creek
Polygon	3	31800	24082200.000001	197	Chico Creek

Record: 0 Show: All Selected Records (0 out of 25 Selected)

Figure 1. Attribute table for the watershed shapefile sorted by area in square meters. A “Shape_Area” of 900 represents just one 30 meter pixel. The large break in size between 13,500 and 1,756,799 helps identify the cutoff between “problem” watersheds.

Landscape Sampling

Landscape sampling was conducted on the calculated watersheds at four spatial scales for all Puget Sound benthic macroinvertebrate sampling locations: (1) within the upstream contributing watershed, (2) within a 1-km radius of the contributing watershed, (3) within a 90-m buffer in the contributing watershed, and (4) within a 90-m buffer in the 1-km contributing watershed (Figure 2).

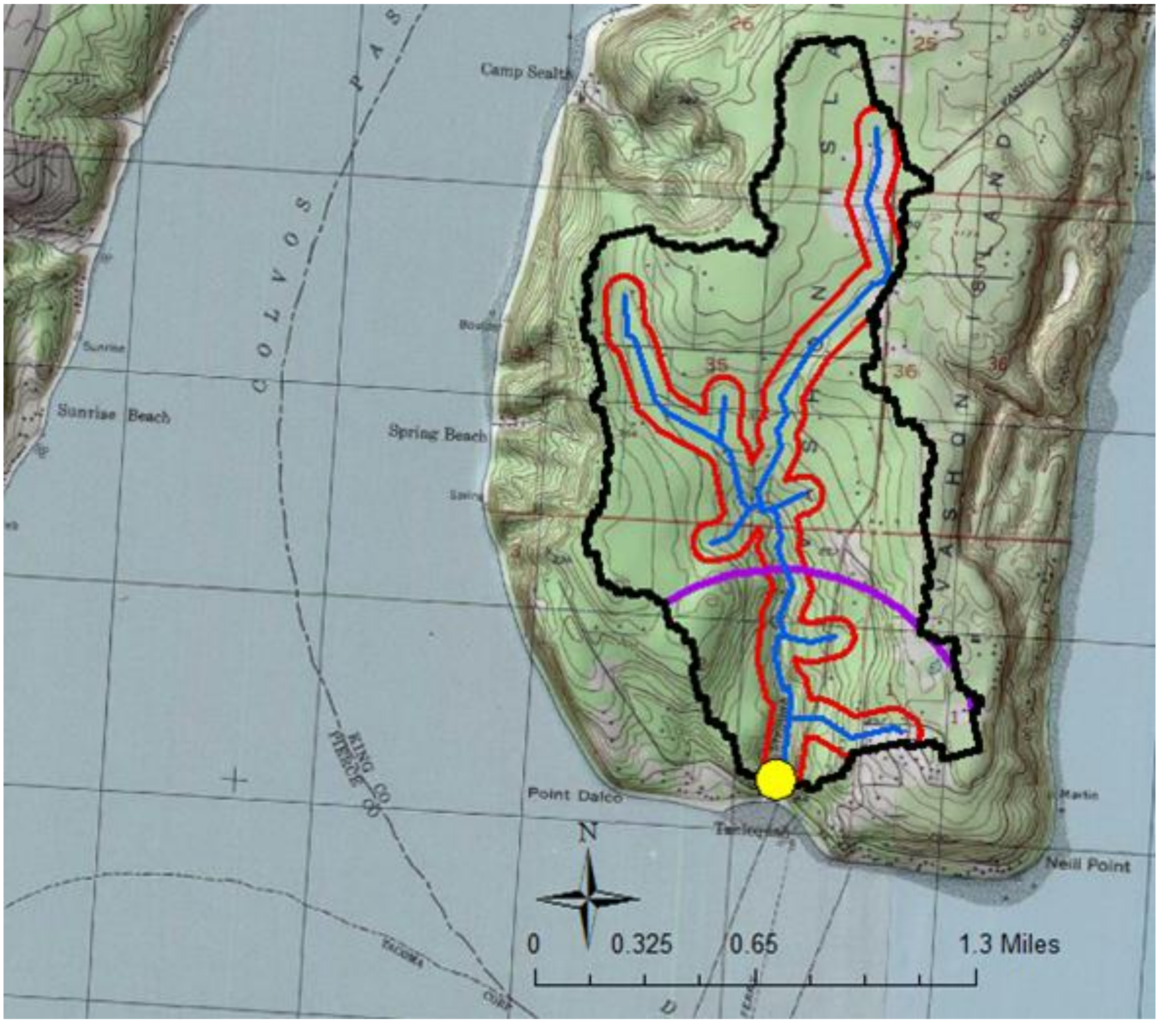

Figure 2. Land use/land cover were evaluated at four spatial scales for each benthic macroinvertebrate sampling location (yellow dot): (1) entire upstream contributing watershed (black line), (2) 90-m buffer within the contributing watershed (red outline), (3) 1-km contributing watershed (purple circle), and (4) 90-m buffer within the 1-km contributing watershed.

Landscape sampling was conducted for these spatial scales using the USEPA GIS Analytical Tools interface for Landscape Assessments (ATtiLA) tool[7].

The following datasets were downloaded and used in the landscape sampling:

1. The 2006 National Land Cover Dataset (NLCD[8]).
    a. The NLCD is a 16-class land cover classification scheme that has been applied consistently across the conterminous United States at a spatial resolution of 30 meters (Fry et al. 2011, Figure 3).
    b. The NLCD dataset was modified using the Change Detection dataset to ensure that current and historic forest harvest areas were classified correctly instead of as grassland or shrub.

[7] ATtILA is an easy to use ArcView extension that calculates many commonly used landscape metrics. http://www.epa.gov/nerlesd1/land-sci/attila/index.htm
[8] 2006 NLCD can be found here: http://www.mrlc.gov/nlcd2006.php.

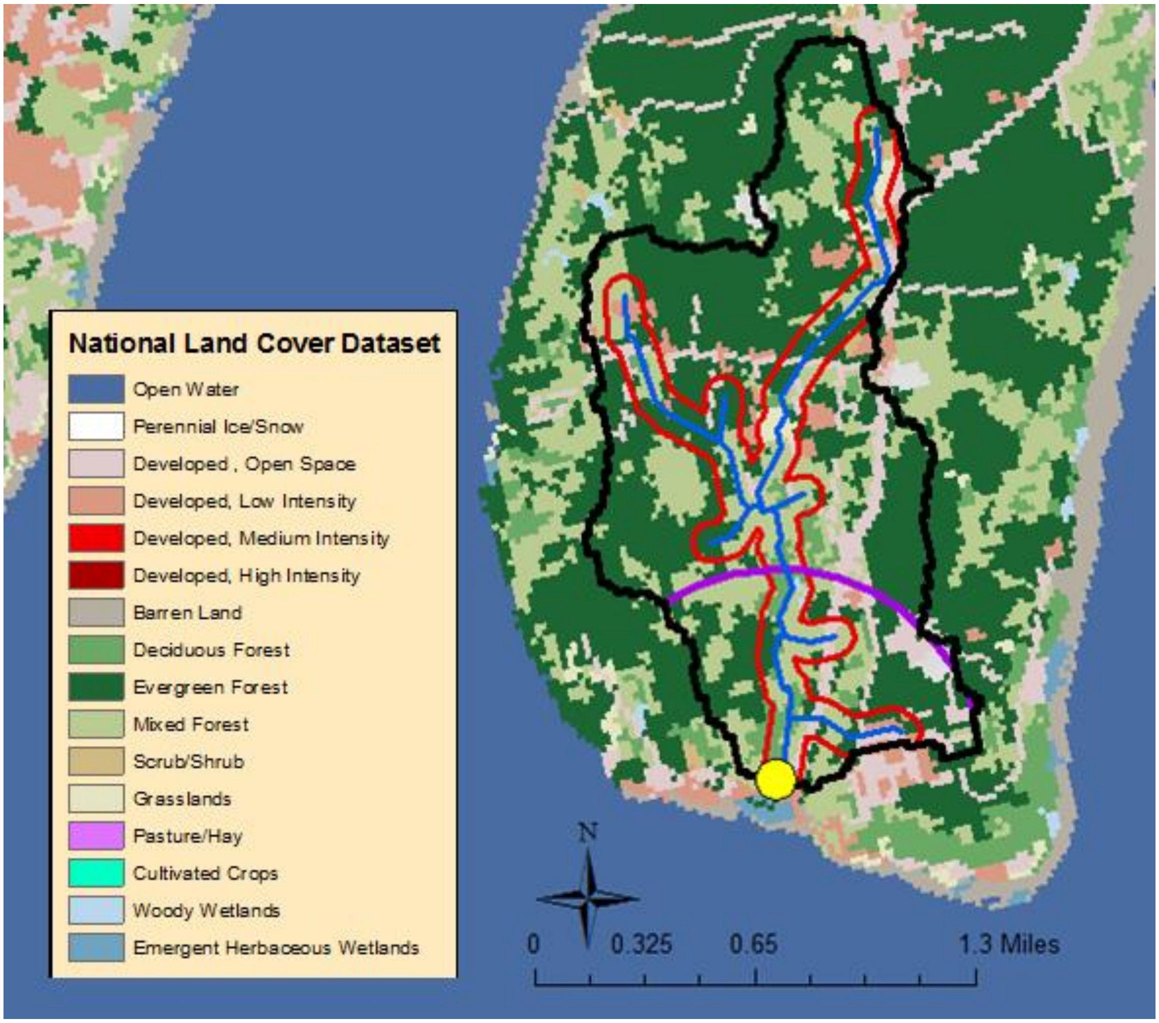

Figure 3. The NLCD is a 16-class land cover classification scheme that has been applied consistently across the conterminous United States at a spatial resolution of 30 meters.

2. Datasets obtained from the USEPA region 10 server:
    a. A roads data set from NAVTEQ roads data set.
    b. 2000 United States census data. Population values were apportioned by area-weighting. For example, if 50% of a census unit was within the reporting unit, 50% of the population was assigned to that reporting unit.
3. Precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) project[9]
4. Data previously downloaded from NHDPlus that were also used in the watershed calculations:
    a. The streams layer
    b. NHDPlus FAC grid[10]
    c. NHDPlus digital elevation model (DEM)

[9] PRISM project: www.prism.oregonstate.edu
[10] NHDPlus FAC grid is preprocessed with flow routes, which ensures more accurate representation of stream locations in flat areas than a 10-m Digital Elevation Models (DEM).

5. Surficial geology
    a. Geology data[11] originated with the Washington Division of Geology and Earth Resources which portrays Washington State Geology at a scale of 1:100,000.
    b. Major geologic units for Puget Sound were characterized into high or low permeability for Puget Sound following the approach employed by the Washington Department of Ecology (Stanley et al. 2005). In the Pacific Northwest, alluvium in lowland areas and glacial outwash are typically composed of coarse-grained sediment and support high levels of permeability.
6. Coastal Change Analysis Program (C-CAP[12]) regional land cover
    a. C-CAP is a nationally standardized database of 25 land cover classifications and land change information for U.S. coastal regions at a 30-m spatial resolution.
    b. Data were downloaded for 1992, 1996, 2001, and 2006.

Table 1 summarizes the landscape metrics calculated divided into human disturbance, physical characteristics, and land cover results.

[11] Geology metadata: http://gisdw/intranet/sdc/nonkcgis/addl_doc/200810snr7002/pages/gunitp100k.htm
[12] C-CAP: http://www.csc.noaa.gov/digitalcoast/data/ccapregional

Table 1. Summary of sampled landscape metrics.

Data Source	Scale	Landscape metrics
2006 NLCD	watershed (all and 1-km) and buffer (90-m, all and 1-km) scale	% forest % non-regeneration forest % regeneration forest % young forest (1992-2002 harvest) % older forest (1972-1992 harvest) % wetland % shrub % grasslands % barren % urban % agriculture
NAVTEQ Roads	watershed scale (all and 1-km), no buffers	total road length (m) road density (km/km^2) # road crossings/km stream total # road crossings
2000 Census		population density ($count/km^2$) total population
PRISM Precipitation		mean, min, max precipitation (mm)
DEM		elevation at pour point (m) mean, min, max elevation (m) mean, min, max % slope
NHD Streams		total stream length (m) stream density (km/km^2)
Physical		watershed and 1-km watershed areas (hectares) longitude and latitude of pour point
Surficial Geology		% High Permeability % Low Permeability
C-CAP (1992, 1996, 2001, 2006)		% Bare, % Snow/Ice, % Tundra, %Water % Ag (Cultivated, Pasture/Hay) % Forest (Deciduous, Evergreen, Mixed) % Urban (Developed open space, high-, medium-, and low-intensity) % Wetland (Estuarine or Palustrine: Aquatic Bed, Emergent, Forested, Scrub/Shrub) % Scrub/Shrub % Grassland

Results

Watershed boundary calculations

1,011 watershed boundaries were initially calculated using the methodology described above for benthic macroinvertebrate sites within the Puget Sound region. The following errors were identified from these watersheds:

- 10 points did not snap to a stream
- 75 points snapped to the wrong stream
- 2 duplicates

Duplicate sites were removed, the watershed boundaries were re-calculated, and a second analysis run was conducted and some additional sites were included resulting in 1,132 watershed boundaries (Figure 4).

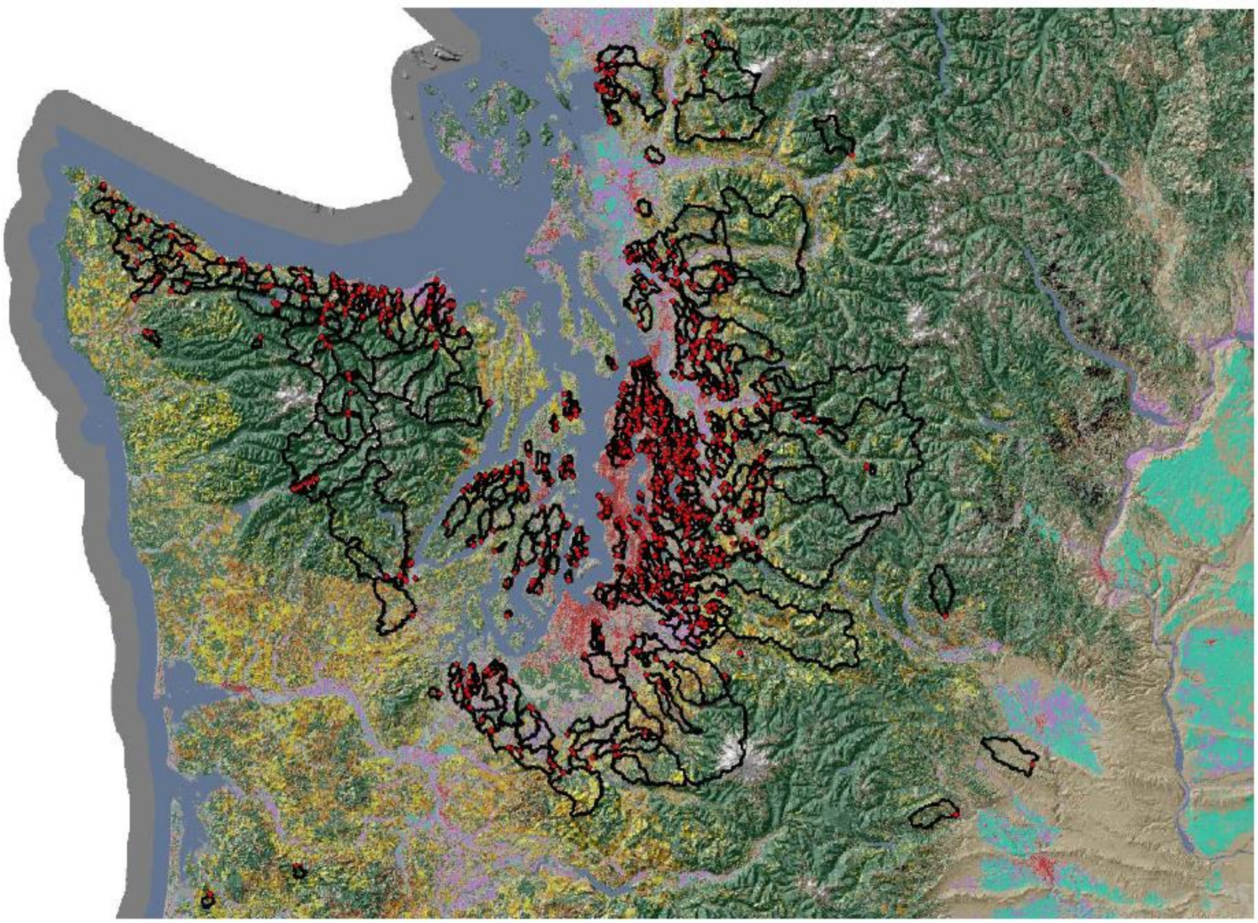

Figure 4. Watershed boundaries for over 1,000 biological monitoring sites within the Puget Sound region.

Landscape characterization

2006 NLCD land cover varied considerably between delineated watersheds. Percent forest for the contributing watershed and the 90-m watershed buffer ranged from 0 to 100, while percent watershed urbanization ranged from 0 to 98 (Table 2). Sampling site elevation ranged from 0 to over 1,000 m. Appendix 1 presents the summary statistics for the calculated landscape metrics.

Table 2. Summary statistics for representative landscape metrics for 1,132 biologic sampling locations. See Appendix 1 for results of all landscape metrics. Contributing watershed is ws; 90-m buffer is bf.

Variables	Mean	Median	Min	Max	Std. Dev.
% Forest (ws)	56.3	64.4	0.0	100	31.8
% Urban (ws)	24.7	8.7	0.0	98	30.1
% Agriculture (ws)	11.8	8.7	0.0	62	11.0
% Forest (bf)	57.4	64.2	0.0	100	30.8
% Urban (bf)	21.8	7.2	0.0	95	27.5
% Agriculture (bf)	12.6	9.8	0.0	87	11.8
Road density (km/km^2) (ws)	4.0	2.3	0.0	18	4.1
Population density ($\#/km^2$) (ws)	483.3	93.9	0.0	3266	733.7
Elevation site (m)	92.3	52.7	0.0	1015	114.6
Watershed area (hectares)	5603.2	906.4	9.2	167650	16166.8
Precipitation mean (mm) (ws)	1575.8	1286.7	432.8	4463	733.4
Density stream (km/km^2) (ws)	2.0	2.0	0.0	7	0.4

The histogram for watershed urbanization presented below demonstrates the distribution of sites across an urbanization gradient (Figure 5); sites with between 0 and 10 percent urbanization are the most common.

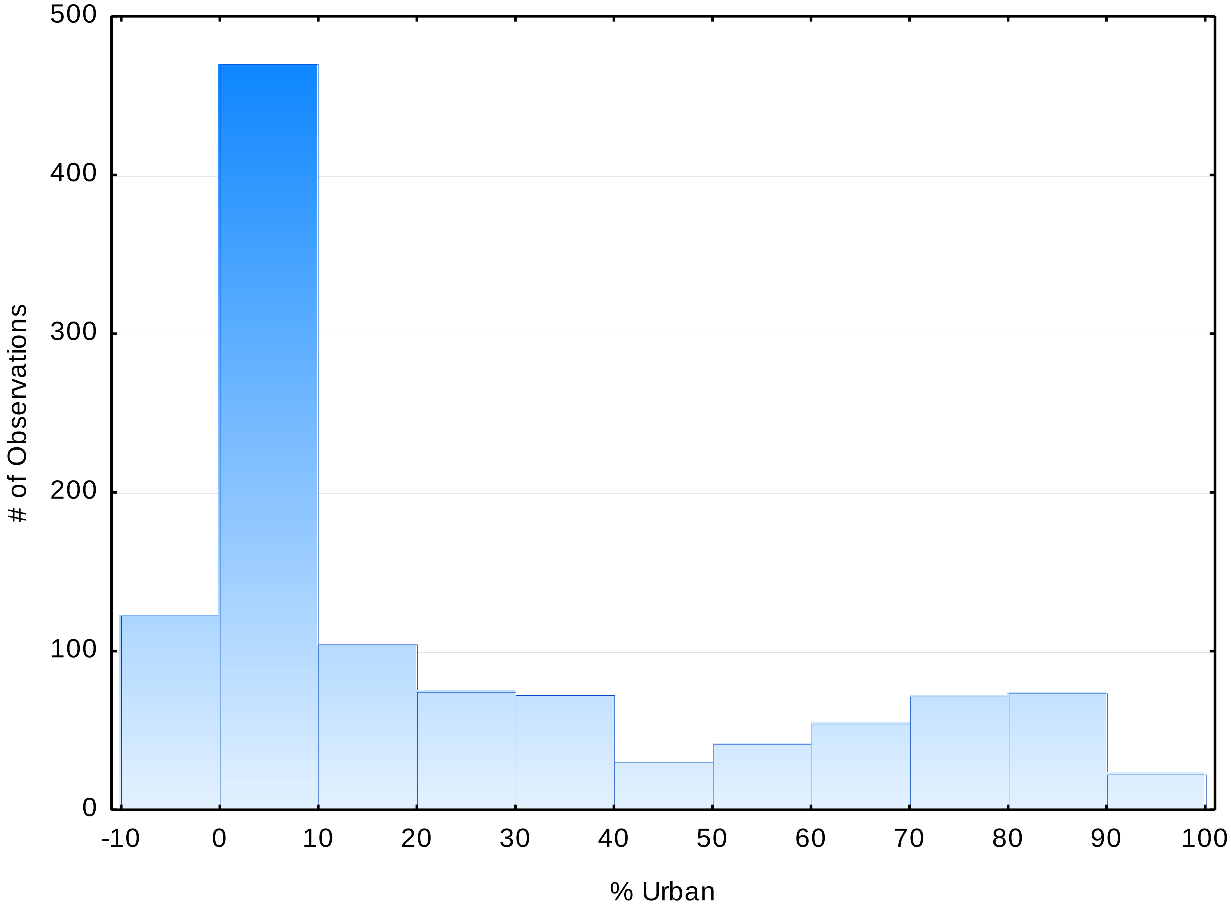

Figure 5. Histogram of percent watershed urbanization. Observations displayed in the -10 to 0 bin represent 0% watershed urbanization.

When land cover is averaged across all watersheds, percent forest is the dominant land cover (Figure 6). Compared to the 1-km contributing watershed (50.7%), the entire watershed scale generally has higher percentages of forest (56.3%). The 90-m buffer land cover is very consistent with the land cover for the comparative watershed or 1-km watershed scale.

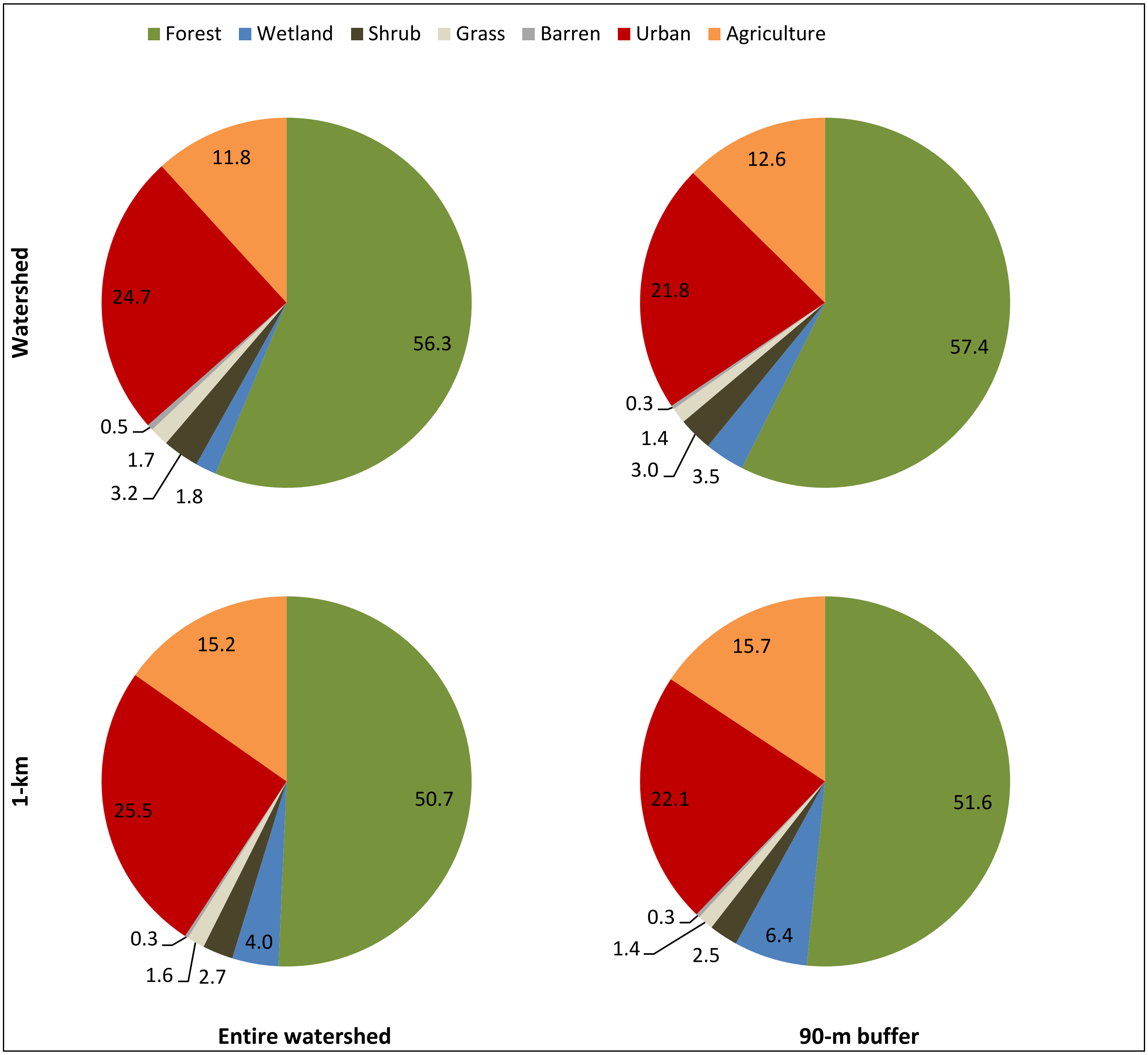

Figure 6. Mean land cover metrics for the four spatial scales for over 1,000 benthic macroinvertebrate sampling locations: contributing watershed (top left), 90-m buffer within the contributing watershed (top right), 1-km contributing watershed (bottom left), and 90-m buffer within the 1-km contributing watershed (bottom right).

Most Puget Sound monitoring locations are at elevations less than 500 m in elevation (Figure 7). The land use/land cover for both the entire Puget Sound basin and the Puget Sound basin from sea level to 500 m were calculated. Puget Sound less than 500 m has slightly less forest (58 vs. 67%) and wetland (3 vs. 6%) and slightly more urbanization (14 vs. 8%) and agriculture (16 vs. 9%) as compared to the entire Puget Sound basin (Figure 8).

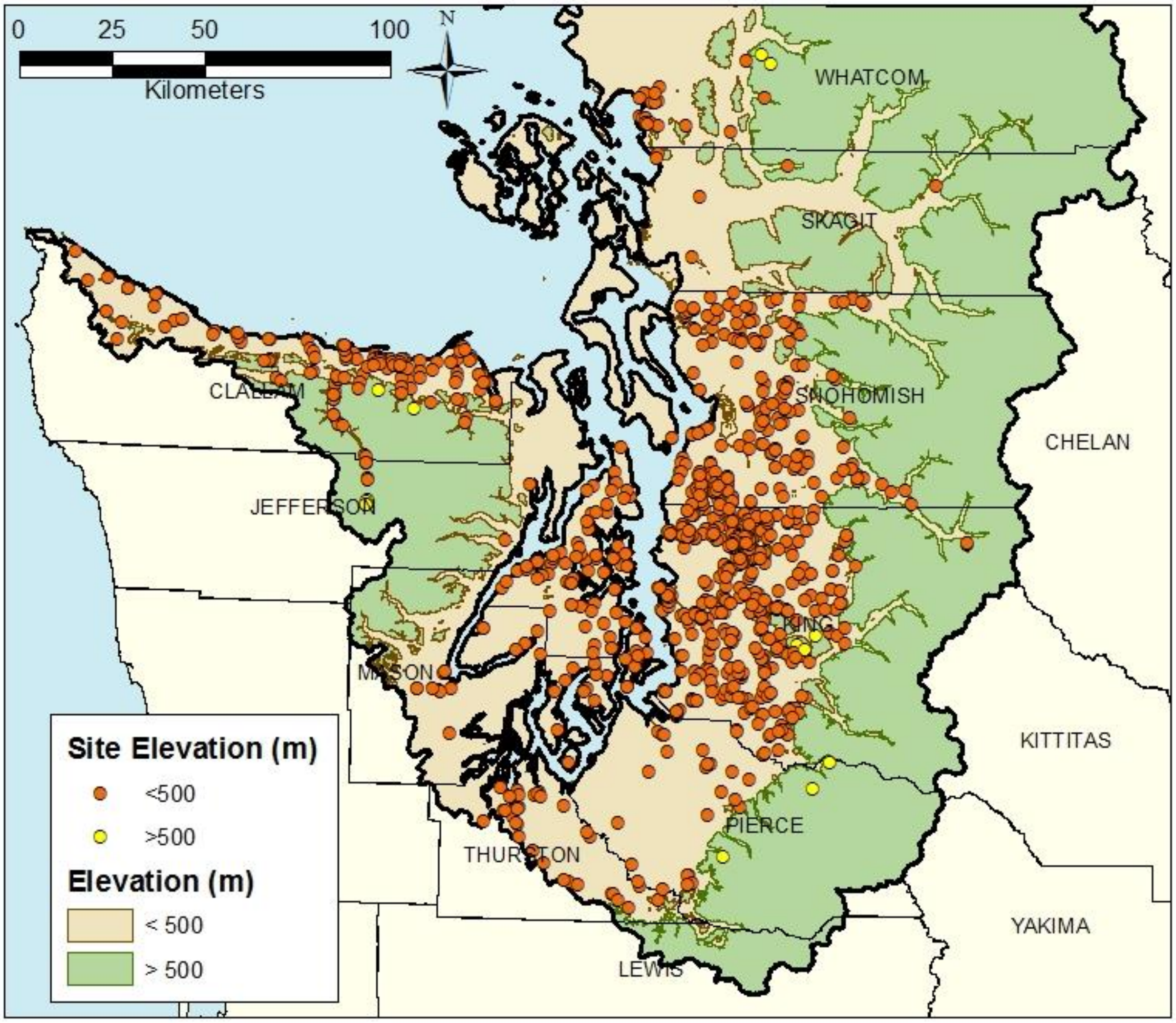

Figure 7. The Puget Sound basin divided into elevations greater than 500 m (green) or less than 500 m (tan). Points shown are biological monitoring locations with data in the PSSB.

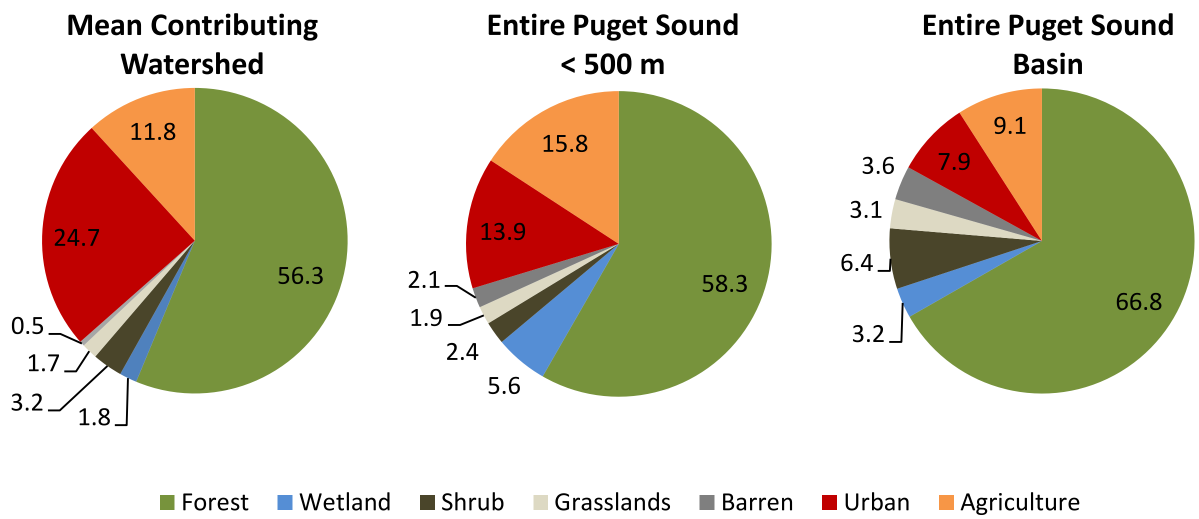

Figure 8. Land use/ land cover for the calculated watersheds (left, also the top left figure in Figure 6), the Puget Sound basin from sea level to 500 m in elevation (center) and the entire Puget Sound basin (right).

Appendices 2 through 5 present the summary statistics for physical characteristics, human disturbance, surficial geology, and C-CAP 2001 to 2006 landcover change.

Conclusions

The automated GIS methods saved a significant amount of time compared to previously tested manual methods. For example, completion of the watershed delineation calculations took approximately two days to complete. Manual analysis of these data would have likely taken weeks to complete. The automated methods correctly delineated over 95% of the watersheds in the first round and additional adjustments were made to increase the final watershed delineation accuracy. The XY points used for the watershed creation were the most accurate points possible to estimate watersheds based on the GIS datasets. However, it was beyond the scope of this project to verify every sampling location with project managers at every agency that contributes data to the PSSB.

The landscape metrics presented in this memo and calculated for over 1,000 Puget Sound watersheds will be used to (1) develop a human disturbance gradient, (2) test invertebrate sensitivity to disturbance (i.e., developing tolerant and intolerant taxa lists), (3) update and rescore each of the ten B-IBI metrics, and (4) test whether any scoring alterations are warranted for some of the physical characteristics (e.g., elevation or slope).

The landscape metric calculations and watershed delineations are available as an Excel file and a GIS shape file, respectively, to be shared with regional partners (download from the PSSB[13]).

[13] Data are available for download: http://www.pugetsoundstreambenthos.org/Projects/Improving-Biological-Monitoring-Tools-Documentation.aspx.

References

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Appendix 1. Summary Statistics for Land Cover Metrics (2006 NLCD).

Table A-1. Summary statistics for 2006 NLCD landscape metrics for 1,132 biologic sampling locations.

Variable Name	Mean	Median	Min	Max	Std. Dev.
% Forest (ws)	56.3	64.4	0.0	100	31.8
% Forest Nregen (ws)	43.7	42.3	0.0	100	27.1
% Forest Regen (ws)	12.5	4.9	0.0	84	16.6
% Forest Young (ws)	3.1	0.5	0.0	71	6.5
% Forest Older (ws)	9.4	3.6	0.0	84	13.3
% Wetland (ws)	1.8	0.9	0.0	36	2.8
% Shrub (ws)	3.2	2.0	0.0	79	4.7
% Grass (ws)	1.7	0.7	0.0	52	2.8
% Barren (ws)	0.5	0.0	0.0	14	1.7
% Urban (ws)	24.7	8.7	0.0	98	30.1
% Agriculture (ws)	11.8	8.7	0.0	62	11.0
% Forest (1 km ws)	50.7	50.1	0.0	100	31.4
% Forest Nregen (1 km ws)	40.8	37.3	0.0	100	27.6
% Forest Regen (1 km ws)	9.9	1.2	0.0	90	17.6
% Forest Young (1 km ws)	2.3	0.0	0.0	71	6.9
% Forest Older (1 km ws)	7.6	0.2	0.0	90	14.7
% Wetland (1 km ws)	4.0	1.5	0.0	67	6.7
% Shrub (1 km ws)	2.7	0.6	0.0	95	6.0
% Grass (1 km ws)	1.6	0.0	0.0	52	3.4
% Barren (1 km ws)	0.3	0.0	0.0	24	1.6
% Urban (1 km ws)	25.5	14.0	0.0	99	28.1
% Agriculture (1 km ws)	15.2	11.3	0.0	83	14.3
% Forest (bf)	57.4	64.2	0.0	100	30.8
% Forest Nregen (bf)	46.3	45.4	0.0	100	27.2
% Forest Regen (bf)	11.2	4.1	0.0	100	15.7
% Forest Young (bf)	2.6	0.2	0.0	100	6.3
% Forest Older (bf)	8.6	3.0	0.0	81	12.7
% Wetland (bf)	3.5	1.7	0.0	100	6.2
% Shrub (bf)	3.0	1.5	0.0	76	4.7
% Grass (bf)	1.4	0.5	0.0	36	2.5
% Barren (bf)	0.3	0.0	0.0	20	1.1
% Urban (bf)	21.8	7.2	0.0	95	27.5
% Agriculture (bf)	12.6	9.8	0.0	87	11.8
% Forest (1km bf)	51.6	53.9	0.0	100	31.0
% Forest Nregen (1km bf)	42.8	41.1	0.0	100	28.2
% Forest Regen (1km bf)	8.7	0.0	0.0	100	17.1
% Forest Young (1km bf)	2.5	0.0	0.0	100	7.3
% Forest Older (1km bf)	6.3	0.0	0.0	92	13.6
% Wetland (1km bf)	6.4	2.3	0.0	100	10.1
% Shrub (1km bf)	2.5	0.0	0.0	92	6.2
% Grass (1km bf)	1.4	0.0	0.0	36	3.4
% Barren (1km bf)	0.3	0.0	0.0	31	1.9
% Urban (1km bf)	22.1	10.8	0.0	98	26.2
% Agriculture (1km bf)	15.7	11.5	0.0	88	15.1

ws = contributing watershed; 1 km ws = 1 km contributing watershed; bf = 90-m buffer for contributing watershed; 1 km bf = 90-m buffer for 1 km contributing watershed; Nregen = non-regeneration forest; Regen = regeneration forest; young forest = harvested 1992-2002; older forest = harvested 1972-1992.

Appendix 2. Summary Statistics for Physical Characteristic Metrics.

Table A-2. Summary statistics for physical characteristic metrics for 1,132 biologic sampling locations.

Variable Name	Mean	Median	Min	Max	Std. Dev.
Total Road Length (km) (ws)	71.7	22.0	0.0	1904.1	144.5
Road Density (km/km^2) (ws)	4.0	2.3	0.0	18	4.1
Roads per Stream Crossing per km (ws)	2.0	1.1	0.0	14	2.3
Total # Roads Per Stream Crossing (ws)	76.9	21.0	0.0	2045	160.8
Total Road Length (km) (1 km ws)	4.1	2.6	0.0	34.3	4.4
Road Density (km/km^2) (1 km ws)	4.3	3.0	0.0	22	4.0
Roads per Stream Crossing per km (1 km ws)	1.9	1.1	0.0	18	2.2
Total # Roads Per Stream Crossing (1 km ws)	5.0	2.0	0.0	64	6.8
Population Density (#/km^2) (ws)	483.3	93.9	0.0	3266	733.7
Tot Population (ws)	6036.4	805.0	0.0	140682	13523.6
Population Density (#/km^2) (1 km ws)	485.2	118.0	0.0	4117	730.8
Tot Population (1 km ws)	453.1	91.6	0.0	6557	788.2

ws = contributing watershed; 1 km ws = 1 km contributing watershed

Appendix 3. Summary Statistics for Human Disturbance Metrics.

Table A-3. Summary statistics for human disturbance metrics for 1,132 biologic sampling locations.

Variable Name	Mean	Median	Min	Max	Std. Dev.
Elevation site (m)	92.3	52.7	0.0	1015	114.6
Watershed area (hectare) (ws)	5603.2	906.4	9.2	167650	16166.8
Watershed area (hectare) (1 km ws)	93.7	92.3	3.0	214	41.1
Elevation minimum (m) (ws)	91.2	51.9	0.0	1015	114.6
Elevation maximum (m) (ws)	601.4	232.6	43.7	4385	632.1
Elevation mean (m) (ws)	296.3	153.5	13.5	1404	292.1
% slope minimum (ws)	0.3	0.0	0.0	20	1.3
% slope maximum (ws)	85.6	56.3	3.6	883	85.5
% slope mean (ws)	17.6	9.8	1.5	83	16.1
Precipitation minimum (mm) (ws)	1298.6	1129.5	393.0	3982	548.7
Precipitation maximum (mm) (ws)	1942.5	1447.0	440.0	6756	1186.4
Precipitation mean (mm) (ws)	1575.8	1286.7	432.8	4463	733.4
Length stream (km) (ws)	109.2	17.8	0.0	3240	311.3
Density Stream (km/km^2) (ws)	2.0	2.0	0.0	7	0.4
Elevation minimum (m) (1 km ws)	91.2	52.0	0.0	1015	114.6
Elevation maximum (m) (1 km ws)	213.9	141.8	13.2	1328	188.9
Elevation mean (m) (1 km ws)	141.4	97.6	6.4	1135	136.7
% slope minimum (1 km ws)	0.6	0.2	0.0	21	1.7
% slope maximum (1 km ws)	47.0	40.7	1.9	225	27.7
% slope mean (1 km ws)	13.9	10.1	0.4	80	11.0
Precipitation minimum (mm) (1 km ws)	1323.4	1156.0	400.0	3982	583.5
Precipitation maximum (mm) (1 km ws)	1420.0	1219.0	421.0	4425	653.0
Precipitation mean (mm) (1 km ws)	1366.4	1185.4	406.9	4150	611.1
Length stream (km) (1 km ws)	2.4	2.2	0.0	7.1	1.2
Density stream (km/km2) (1 km ws)	2.6	2.5	0.0	47	1.6

ws = contributing watershed; 1 km ws = 1 km contributing watershed

Appendix 4. Summary Statistics for Surficial Geology Permeability.

Table A-4. Summary statistics for surficial geology permeability for 1,132 biologic sampling locations.

Variable Name	min	max	average	median	std dev
High Permeability (1 km ws)	0.0	100.0	44.3	42.3	34.4
Low Permeability (1 km ws)	0.0	100.0	55.3	57.7	34.5
Water (1 km ws)	0.0	25.6	0.4	0.0	2.0
High Permeability (ws)	0.0	100.0	24.0	17.8	23.8
Low Permeability (ws)	0.0	100.0	75.4	81.4	24.0
Water (ws)	0.0	18.5	0.6	0.0	1.8

ws = contributing watershed; 1 km ws = 1 km contributing watershed

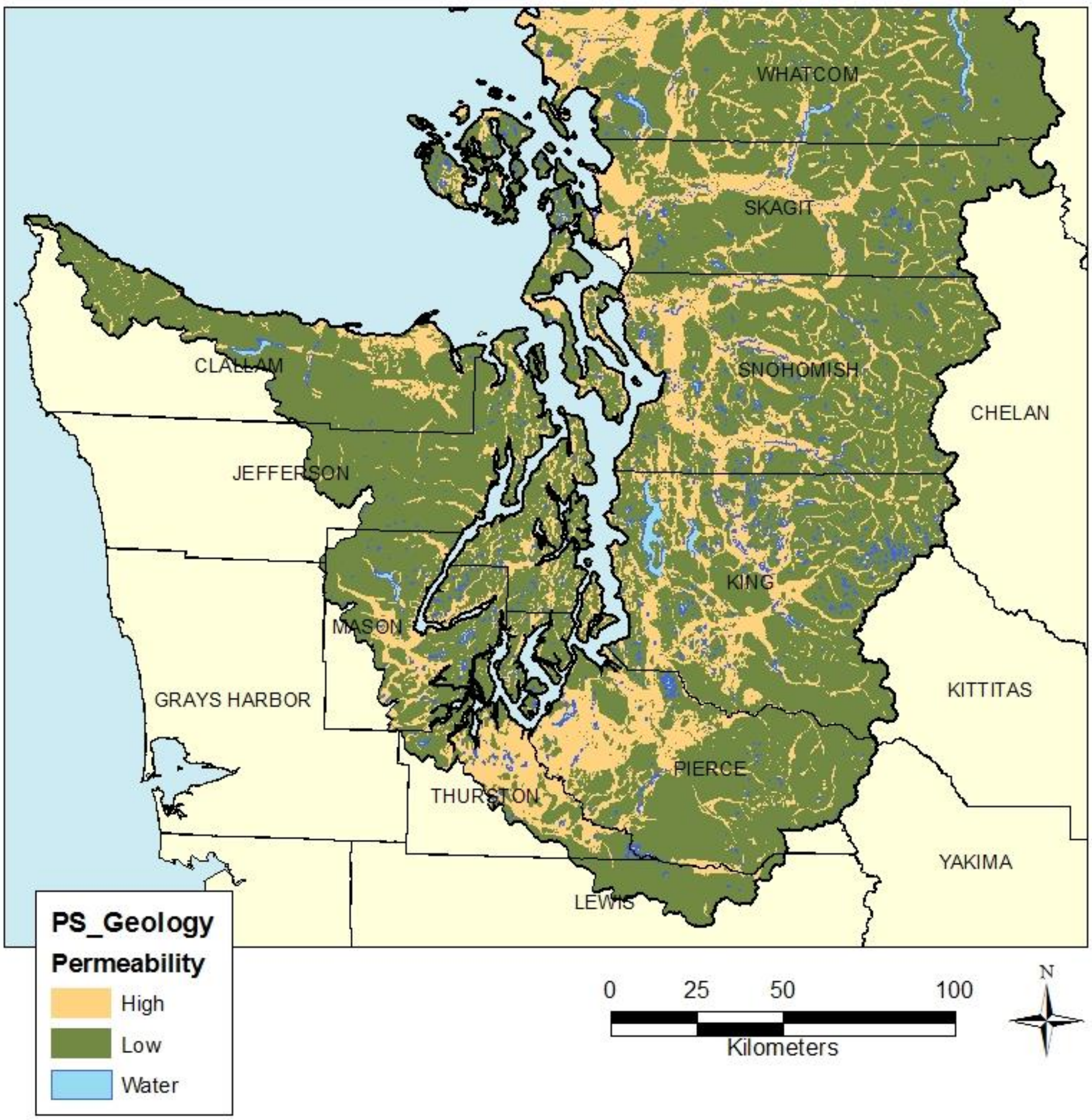

Figure A-4. Surficial geology permeability for Puget Sound.

Appendix 5. C-CAP Land Cover Change.

Table A-5. Summary statistics for land cover change between 2001 and 2006. 2001 to 2006 was selected because most benthic macroinvertebrate data from the PSSB is from this approximate time frame.

Variable Name	min	max	average	median	std dev
Urban (1km ws)	0.0%	38.0%	0.6%	0.0%	2.9%
Urban (ws)	0.0%	45.8%	0.8%	0.0%	2.8%
Forest (1km ws)	-60.7%	38.1%	-0.8%	0.0%	4.8%
Forest (ws)	-60.7%	24.7%	-1.2%	-0.2%	4.0%
Natural LC (1 km ws)	0.1%	11.1%	1.8%	0.6%	2.6%
Natural LC (ws)	0.0%	9.2%	0.8%	0.1%	1.7%

ws = contributing watershed; 1 km ws = 1 km contributing watershed. Natural = forest, wetland, scrub-shrub, and grassland combined. Forest = mixed, deciduous, evergreen. Urban = developed open space, high, medium, and low density development.

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