Development of An Empirical Water Quality Model for Stormwater Based on Watershed Land Use in Puget Sound

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Introduction

The Sinclair and Dyes Inlet watershed is located on the west side of Puget Sound in Kitsap County, Washington, U.S.A. (Figure 1). The Puget Sound Naval Shipyard (PSNS), U.S Environmental Protection Agency (USEPA), the Washington State Department of Ecology (WA-DOE), Kitsap County, City of Bremerton, City of Bainbridge Island, City of Port Orchard, Suquamish Tribe and other stakeholders have joined in a cooperative effort to evaluate water-quality conditions in the Sinclair-Dyes Inlet watershed and correct identified problems. A major focus of this project, known as Project ENVVEST, is to develop Water Quality Improvement Projects (also known as Total Maximum Daily Loads – TMDLs) for constituents listed on the 303(d) list within the Sinclair and Dyes Inlet watershed (Johnston 2004). Segments within the Sinclair and Dyes Inlet watershed were listed on the State of Washington's 1998 303(d) because of fecal coliform contamination in marine water, metals in sediment and fish tissue, and organics in sediment and fish tissue (WA-DOE 2003). Stormwater loading was identified by ENVVEST as one potential source of sediment contamination, which lacked sufficient data for a contaminant mass balance calculation for the watershed.

This paper summarizes the development of an empirical model for estimating contaminant concentrations in all streams and outfalls discharging into Sinclair and Dyes Inlets. The model is based on current watershed land use and data collected during 18 storm events, and wet/dry season baseflow conditions between November 2002 and May 2005. Stream pollutant concentrations along with estimates for stormwater outfalls and surface runoff will be used in estimating the loading and ultimately in establishing a Water Cleanup Plan (TMDL) for the Sinclair-Dyes Inlet watershed.

Event Sampling

Baseflow water quality conditions were determined for representative marine stations, streams, and stormwater outfalls (Figure 1) during summer dry season baseflow (DSBF: May thru October) and winter wet season baseflow (WSBF: November thru April) in 2001 and WSBF in 2005. Eighteen storm events were sampled at representative locations in streams, outfalls, and marine waters. Storms were classified based on the total event rainfall as small (0.1-0.5 inches), medium (0.5-1.0 inch), medium-large (1-2 inches), or large (> 2 inches). The antecedent dry period (ADP) ranged from 1 to 22 days. The distribution of storms sampled was representative of both the historic rainfall patterns and precipitation that occurred during the study period (WY 2003-2005) based on precipitation analyses conducted by Halkola (2004 and 2006).

Storm-event sampling was conducted over a three-year period during the winter storm seasons of 2003, 2004, and 2005. automated samplers (ISCO Model 6700) were used wherever possible to collect stormwater samples as time-paced composites for streams and flow-weighted, time-paced composites for outfalls. If autosamplers were not available, grab samples were collected during three periods of the storm (first hour, anticipated peak, and tailing). Additional information on field sampling is available in Johnston et al. 2005 and Brandenberger *et al*. (2007).

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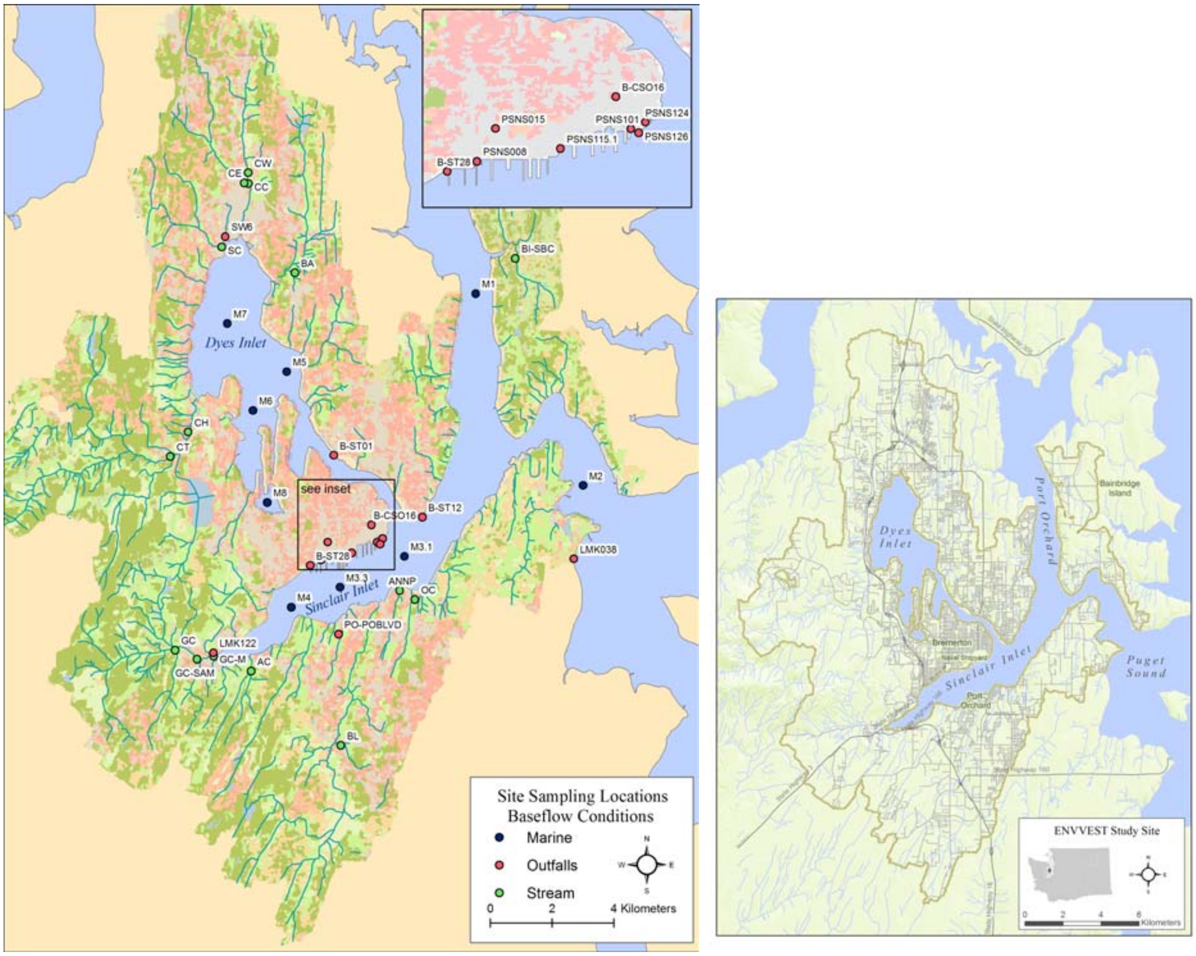

Figure 1 Sinclair-Dyes Inlet watershed study area with sampling locations for streams, outfalls, and marine stations.

All equipment and handling protocols, both in the field and laboratory, were based on observing ultra-clean techniques for water sample collection following United States Environmental Protection Agency (USEPA) Method 1669 Sampling Ambient Water for Trace Metals at EPA Water Quality Criteria Levels. Field blanks were collected to evaluate the potential contamination of the samples during collection, transport, and processing at the laboratory. Half of each sample for metals chemistry was filtered through a 0.45μm pre-cleaned cellulose nitrate filter in a Class 100 clean bench to produce the "dissolved" fraction. USEPA methods or National Oceanic and Atmospheric Administration (NOAA) Status and Trends Methods (NOAA 1998) were used or adapted for performance enhancement for all contaminants. A detailed description of all analytical methods is provided in Brandenberger *et al*. (2007).

Statistical Model Development

Watershed landscape characteristics have an influence on the suite of pollutants found in runoff, the concentrations of those pollutants, and, therefore, the water-quality constituent concentrations found in receiving waters (Burton and Pitt 2002; Smullen and Cave 2002; Novotny 2003; Pitt et al. 2004). Based on the known relationship between watershed land-use and land-cover (LULC) characteristics and water quality, specific correlations were developed for the study area. Data from sampled streams and stormwater outfalls were used to develop water quality-LULC correlations, which were used to estimate pollutant concentrations for a loading model. Only the stream model development will be presented here.

The statistical analysis methods used in this project were developed as part of an earlier Sinclair-Dyes Inlet watershed bacterial contamination assessment project (May et al. 2005).

LULC in the Sinclair-Dyes Inlet watershed was analyzed using the 1999 Landsat-7 Thematic Mapper (TM) data and geographic information system software (GIS) with 30-meter pixel resolution. In addition, a more recent (2002) parcel-based LULC data set was used to check for significant changes within the watershed and to validate the Landsat data. Pixels were classified into 25 LULC categories that included types of development, vegetative cover, water, and hard and natural surfaces. The percent cover of each LULC category was calculated for each stream sub-basin and 100-m riparian buffer. Total impervious area for each sub-basin was calculated using standard conversion factors for the Puget Sound region determine based on Hill et al. (2000).

The concentrations from sampled streams were used to estimate the concentrations from watersheds that were not sampled; therefore, a comparison of the sample characteristics to the larger study area was conducted. Both the coefficient of variability (CV = standard deviation/mean x 100%) and the distribution of landscape characteristics between the sample sites and the entire landscape population encompassed in the study area were used to assess the representativeness of the sample sites with respect to the population of interest. First and third quartiles of LULC (%) characteristics for both data sets were normalized (dividing by the median LULC% value for the full study area) so that all variables could be plotted on a similar scale. A representative sample would be expected to have less bias in the estimation process.

The correlation matrix between each pair-wise water quality (WQ) constituent and LULC variable was calculated for dry-season and wet-season baseflow conditions, as well as for storm-event size categories. Correlations with a magnitude greater than $r = 0.60$ were considered relevant for modeling purposes. Scatter plots of the WQ constituent concentrations and LULC variables were used to evaluate possible outliers or anomalous observations. Consistent patterns observed between similar WQ constituents provided confidence in inferring trends when data was limited across a level of development or storm event size. Watershed landscape clusters were based on the three levels of development (low, moderate, and high) and were consistent with those used for estimating fecal coliform bacteria loads in the Sinclair-Dyes Inlet watershed (May and Cullinan 2005).

Estimation of constituent concentrations was based on the combined relationships between storm-event and the LULC cluster characteristics. For each event-size and level of development combination, the WQ sample quartiles were used to “bound” (interval estimation) the WQ concentration. For storm-events, the event-mean concentration was utilized for WQ constituent concentrations. The mean squared error of the observed constituent concentration from the median of the group WQ was used to assess the quality of the estimate for a given constituent and pinpoint potential anomalies.

Results

Percent total impervious area (%TIA) was highly correlated with the sum of moderate-density (suburban) and high-density (urban) residential development and industrial-commercial development for sampled streams and all streams within the study area ($r = 0.98$ and 0.97 respectively; Figure 2). The coefficient of variability (CV) of the percent cover of each landscape variable for sampled streams was slightly smaller but followed a similar pattern to that for all streams in the study area (Figure 3A). The median CV between streams for all sub-basin LULC variables was 63% for the sample and 82% for all streams. Normalized quartiles for stream landscape characteristics were similar to the overall modeled population except for percent rural cover which comprises 5% of the study area (Figure 3B). Therefore, it can be concluded that the sampled sub-basins were representative of the overall landscape of the Sinclair-dyes Inlet watershed study area.

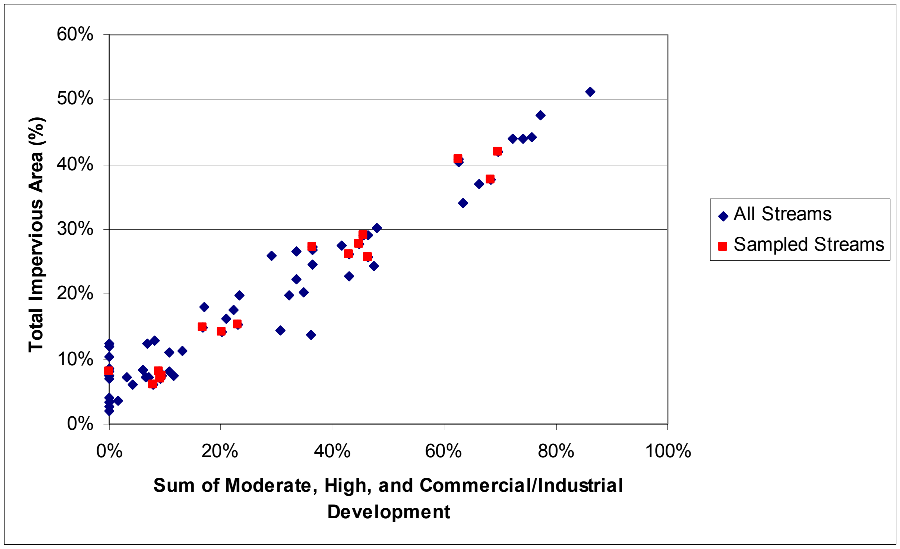

Figure 2. The correlation between the percent total impervious area (%TIA) associated with sampled streams (n=16) and all streams (n=68) and the level of development.

The dry-season baseflow WQ measurements of metal concentrations were not highly correlated with any LULC variables. As an example, Figure 4 depicts the correlations of the concentrations of total copper (Cu) and zinc (Zn) with the sub-basin percent cover of rural and agricultural land (Rural+Ag); forest (%Forest); the sum of moderate, high, and commercial/industrial development (%Developed); %TIA; road density; commercial/industrial development (%Comm+Industrial); and forest in the 100 m riparian buffer (RB100-%Forest). The wet-season baseflow WQ measurements were highly positively correlated with the amount of development within the riparian buffer and negatively correlated with the quantity and type of forested area within the riparian buffer. Dissolved metals tended to be more highly correlated with the buffer characteristics than the total metals, except for Zn and mercury.

Stream WQ measurements taken during small storm events showed total chromium, lead, and Zn as highly correlated with sub-basin scale development, total impervious area (%TIA), and road density. The total metals tended to be more highly correlated to the LULC variables than the dissolved metal components. WQ measurements taken during medium storm events showed high correlations of total metals with sub-basin LULC characteristics and high correlations of dissolved metals with LULC characteristics within the riparian buffer. WQ measurements taken during medium-large storm events tended to show that dissolved metals were more correlated than total metals with measures of sub-basin development. Large storm events had the greatest number of highly correlated WQ measurements with LULC variables. Dissolved components of Cu and lead were more highly correlated to both the sub-basin and riparian buffer characteristics than the total metal concentrations. Both the total and dissolved components of Zn were highly correlated to measures of development for both the sub-basin and riparian buffer scales of analysis. Interestingly, during large storm events, road density was the least correlated LULC parameter with the suite of WQ measurements.

Estimation of constituent concentrations for the loading analysis was defined by a step-function which allowed consistency between WQ measurements that were highly variable and inconsistent in their behavior as a function of rainfall and level of development. The step-fuction for total Cu is provided as an example in Figure 5. Alternatively, a smooth functional response, including the form of the model such as linear or nonlinear, would have to be different for each WQ constituent and level of development. Further, if all constituents were modeled as linear or nonlinear functions, the high degree of variability in

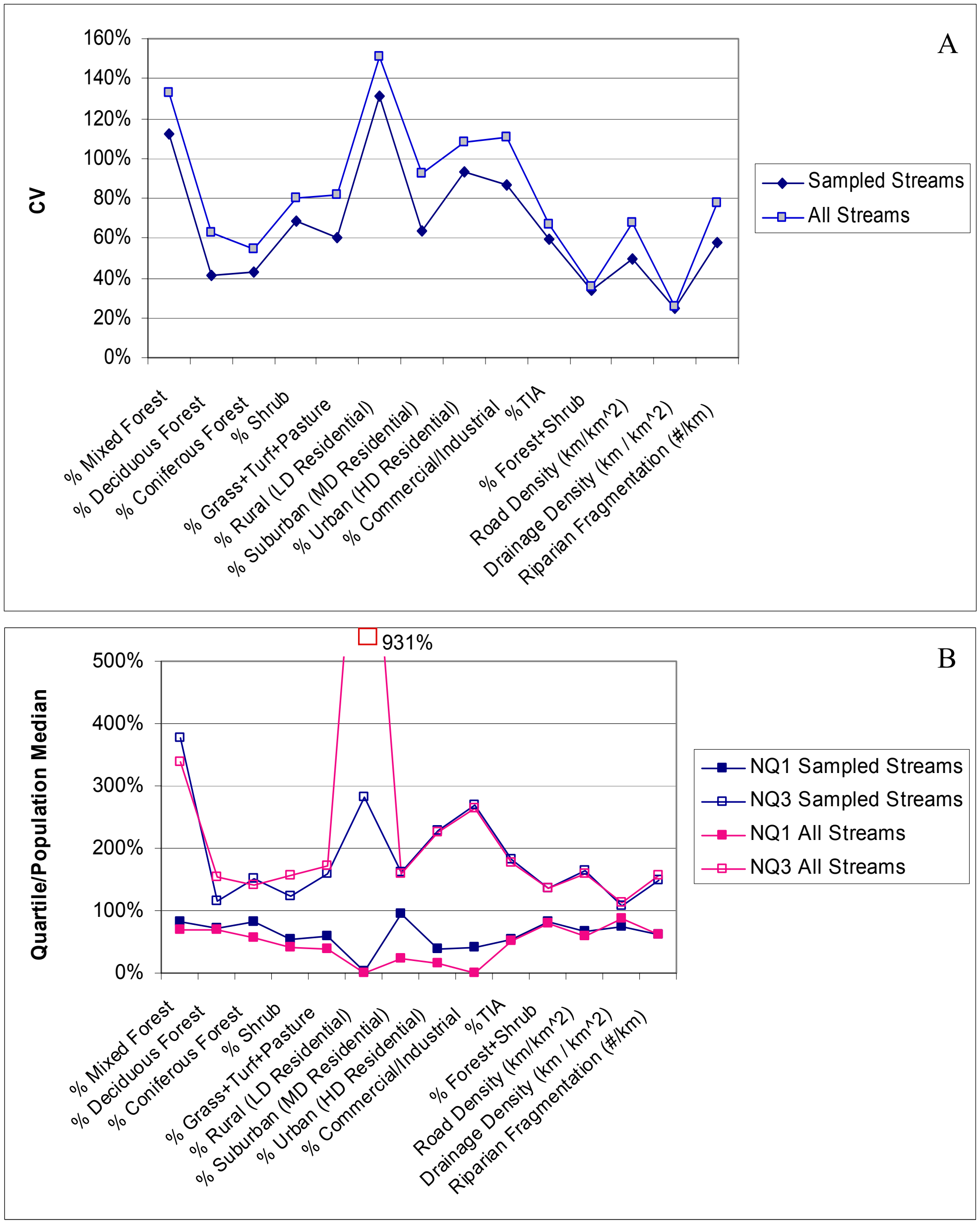

Figure 3. Coefficient of variation (CV) of the landscape characteristics for streams with water quality measurements and for all streams within the study area (A) and quartiles of stream landscape characteristics normalized by the study area median where NQ1 and NQ3 are the 1st normalized quartile and 3rd normalized quartile respectively (B)

the observations and the small sample sizes would make it difficult to have a reasonable level of confidence in the parameter estimates or the choice of model form. Therefore, the step-function model provides the best representation of the data requiring the least amount of parameters and model assumptions (in accordance with Occam's razor). A complete description of all modeling results is provided in Brandenberger et al. (2007).

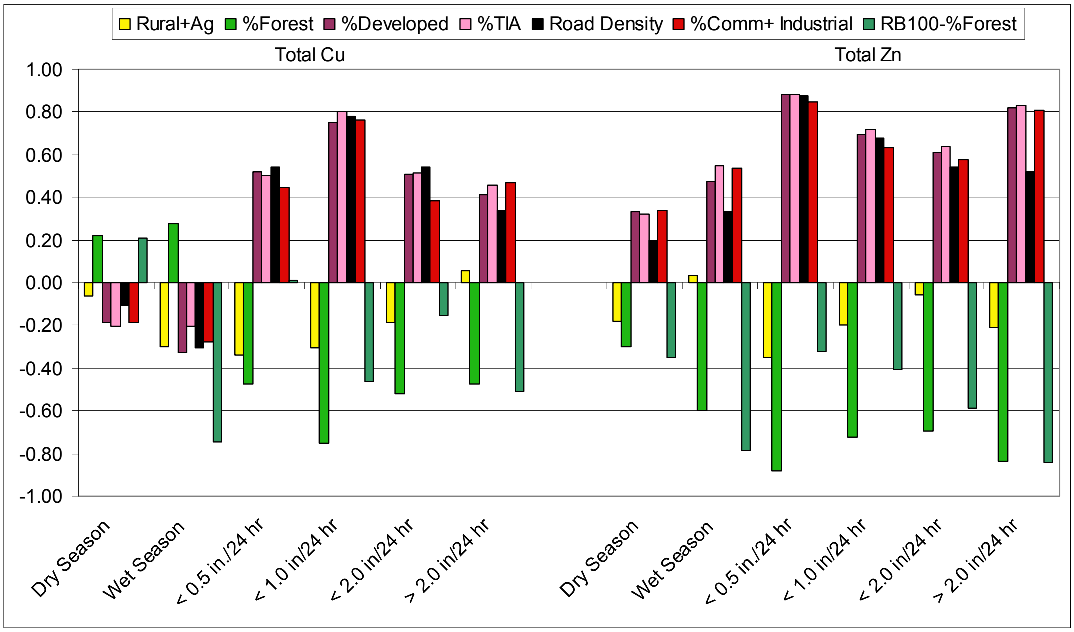

Figure 4. Correlation between each pair-wise LULC variable and total copper (Cu) and zinc (Zn) for dry- and wet-season baseflow conditions (n=15 and 8 respectively), and for each storm-event size category (n=27, 27, 17, and 12 respectively).

Errors associated with estimating constituent concentrations with the step-function model were measured as the sum of the squared difference between the observed and the expected value all divided by the number of observations (MSE; Figure 6). Because the scale of the WQ measurements differed between constituents by orders of magnitude, the maximum observed value for each constituent was also presented. A relative comparison of error between constituents was calculated by dividing the square root of the MSE by the average observed concnetration to obtain a coefficient of error (CE, this form is similar to the calculation of a CV). This analysis suggested that most constituents were estimated with relatively equivalent error. The exception was cadmium which had the greatest CV% of all the metals.

Conclusion

An empirically-based model of water quality as a function of LULC and the amount of rainfall within 24 hours was successfully developed for the Sinclair and Dyes Inlet Watershed. Sampled sub-basins were highly representative of the sub-basins that empty into the Inlets. Stream WQ measurements were highly variable and inconsistent in their behavior as a function of storm event size and LULC. A step-function based on the sampled distribution of stream WQ constituent concentrations, levels of development, and the amount of rainfall allowed water-quality parameters to be estimated for the entire watershed without having to monitor all sources. As part of this study, an integrated watershed-receiving water model was developed to predict pollution levels for a wide range of land-use scenarios. This study was conducted to provide the technical information needed to continue current water quality cleanup efforts and to help implement future efforts to protect and restore beneficial uses. This approach holds great promise for use in other areas of Puget Sound.

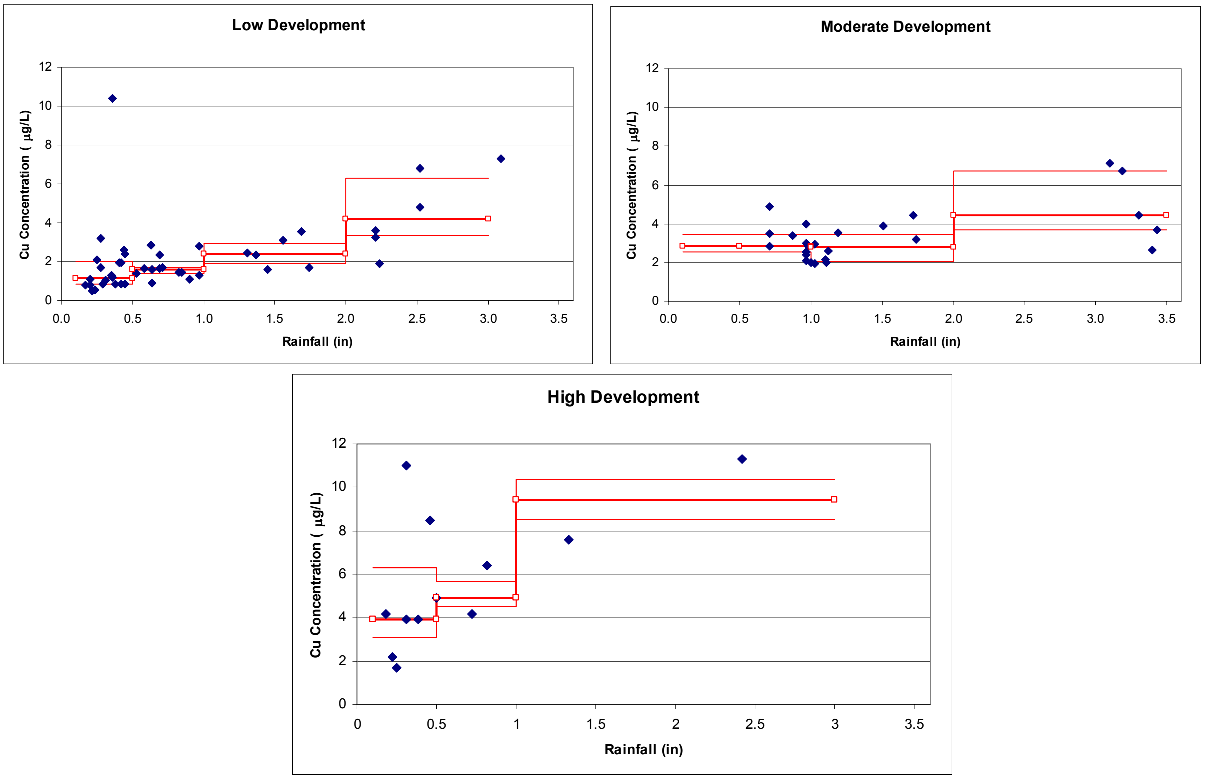

Figure 5. Step-function for total copper (Cu) concentrations based on sample quartiles, level of development (Low, Moderate, and High), and the amount of rainfall within 24 hours.

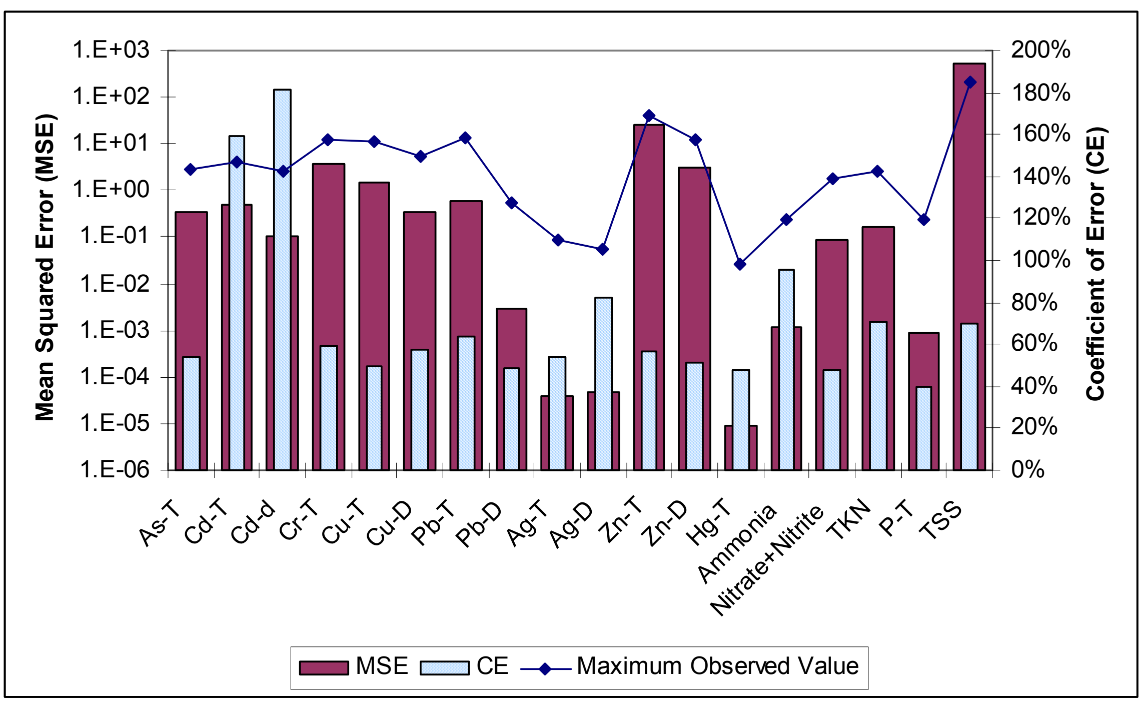

Figure 6. Mean squared error (MSE) and coefficient of error (MSE/mean concentration x 100%) from the step-function estimates for stream WQ measurements and maximum observed concentration which provides a measure of scale for the MSE.

References

Brandenberger, J.M., C.W. May, V.I. Cullinan, R.K. Johnston, 2007, Surface and Stormwater Quality Assessment for Sinclair and Dyes Inlet, Washington. Prepared for Project ENVVEST by Pacific Northwest National Laboratory. (in prep).

Burton, G.A., and R.E. Pitt, 2002, Stormwater Effects Handbook, Lewis Publishers, CRC Press, Boca Raton, FL.

Halkola H., 2004, Analysis of Precipitation Data from the ENVVEST Study Area for Water Year 2003, Appendix C of May et al. 2005.

Halkola H., 2006, Precipitation Analysis Report II, Water Year 2004, Space and Naval Warfare Systems Center, Draft Report, September 2006, San Diego, CA.

Hill K., E. Botsford, and D. Booth, 2000, A Rapid Land Cover Classification Method for use in Urban Watershed Analysis, University of Washington, Center for Urban Water Resources Management (CUWRM) Report, Seattle, Washington.

Johnston, R.K. 2004. PSNS & IMF Project ENVVEST is Helping Improve Environmental Quality In Sinclair and Dyes Inlets, WA. Marine Environmental Update, Summer FY04.

Johnston, R.K., J. Brandenberger, C.W. May, V.S. Whitney, J.M. Wright, B. Beckwith, and R. Pingree 2005. Storm Event Sampling in the Sinclair and Dyes Inlet Watershed: FY2005 Quality Assurance Project Plan. Prepared by Puget Sound Naval Shipyard & Intermediate Maintenance Facility Project ENVVEST For Washington State Department of Ecology Assessments Sections. Jan 18, 2005. http://www.ecy.wa.gov/programs/wq/tmdl/sinclair-dyes_inlets/sinclair_cd/Reports/W2005_QAPP_F.pdf

May, C.W., and V.I. Cullinan, et al. 2005, An Analysis of Microbial Pollution in the Sinclair-Dyes Inlet Watershed, PNNL-15373, Pacific Northwest National Laboratory, Richland, WA and Washington State Department of Ecology Report 05-03-042. http://www.ecy.wa.gov/biblio/0503042.html

NOAA, 1998, Sampling and Analytical Methods of the National Status and Trends Program Mussel Watch Project: 1993-1996 Update, NOAA Tech. Memo. NOS ORCA 130. Silver Springs, MD. 257pp.

Novotny, V., 2003, Water Quality: Diffuse Pollution and Watershed Management, John Wiley and Sons Publishing, NY.

Pitt, R., A. Maestre, and R. Morquecho, 2004, The National Stormwater Quality Database (NSQD) Version 1.1 Report. University of Alabama, Department of Civil and Environmental Engineering, Tuscaloosa, AL.

Smullen, J.T. and K.A. Cave, 2002, National stormwater runoff pollution database, in Wet-Weather Flow in the Urban Watershed. Lewis Publishers, Boca Raton. FL. p 67-78.

USEPA, 1996a, Method 1669, Sampling Ambient Water for Determination of Trace Metals in Environmental Samples, Report No. 821R96011, 36pp.

Washington State Department of Ecology (WA-DOE), 2003, Water Quality Standards for Surface Waters of the State of Washington Chapter 173-201A-WAC, Washington Department of Ecology, Olympia, Washington.