

## **Estimating risks for water-quality exceedances of total-copper from highway and urban runoff under predevelopment and current conditions with the Stochastic Empirical Loading and Dilution Model (SELDM)**

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### **ABSTRACT**

The Stochastic Empirical Loading and Dilution Model (SELDM) was used to demonstrate methods for estimating risks for water-quality exceedances of event-mean concentrations (EMCs) of total-copper. Monte Carlo methods were used to simulate stormflow, total-hardness, suspended-sediment, and total-copper EMCs as stochastic variables. These simulations were done for the Charles River basin upstream of Interstate 495 in Bellingham, Massachusetts. The hydrology and water quality of this site were simulated with SELDM by using data from nearby, hydrologically similar sites. Three simulations were done to assess the potential effects of the highway on receiving-water quality with and without highway-runoff treatment by a structural best-management practice (BMP). In the low-development scenario, total copper in the receiving stream was simulated by using a sediment transport curve, sediment chemistry, and sediment-water partition coefficients. In this scenario, neither the highway runoff nor the BMP effluent caused concentration exceedances in the receiving stream that exceed the once in three-year threshold (about 0.54 percent). In the second scenario, without the highway, runoff from the large urban areas in the basin caused exceedances in the receiving stream in 2.24 percent of runoff events. In the third scenario, which included the effects of the urban runoff, neither the highway runoff nor the BMP effluent increased the percentage of exceedances in the receiving stream. Comparison of the simulated geometric mean EMCs with data collected at a downstream monitoring site indicates that these simulated values are within the 95-percent confidence interval of the geometric mean of the measured EMCs.

### **INTRODUCTION**

Decisionmakers have become increasingly aware of the importance of considering random variation in the quantity and quality of highway runoff, urban runoff, and upstream stormflows for estimating the potential adverse effects of runoff on receiving waters (U.S. Environmental Protection Agency, 1985, 1998, 2002, 2014; Novotny, 2004; Langseth and Brown, 2011). The Stochastic Empirical Loading and Dilution Model (SELDM) uses Monte Carlo methods to generate stormflows, concentrations, and loads from a site of interest and an upstream basin (Granato, 2013a). SELDM is a lumped-parameter mass-balance model that simulates the quality and quantity of runoff from a site of interest and the quality and quantity of total stormflow from an upstream basin. As such, SELDM provides risk-based information needed to assess the

potential for adverse effects of runoff in receiving waters and the potential effectiveness of mitigation measures to reduce these risks.

Although trace metals, including copper, are of primary concern for evaluating the potential effects of stormwater on receiving streams (National Academy of Sciences, 2009), reliable data for concentrations of trace metals in receiving streams during stormflow events are not commonly available. Trace-metal sampling studies in the 1990's showed that methods for collection and processing water samples from streams and rivers for analysis of trace metals caused substantial bias and variability in analytical results and therefore much of the existing trace-metal data for receiving waters was suspect (Horowitz and others, 1994; Benoit and others, 1997, Breault and Granato, 2003). Concentrations of trace metals in sediment samples and whole water samples from runoff and receiving waters commonly are much greater than dissolved (filtered) water concentrations. Furthermore, whole-water concentrations for trace elements are expected to be more robust than filtered water concentrations because of the additional bias and variability caused by filtration processes (Breault and Granato, 2003). Therefore, sediment and whole-water concentrations commonly are considered to be more reliable than dissolved concentrations (Breault and Granato, 2003). However, the methods and materials needed for collecting high-quality data are expensive and the costs for using proper sampling methods have limited data collection efforts in subsequent years (Granato and others, 2009). Therefore, methods were needed to simulate event-mean concentrations (EMCs) for trace metals, such as total-copper, in receiving streams during storm events.

The purpose of this case study was to demonstrate methods for simulating total-copper concentrations in highway runoff with and without stormwater best management practices (BMPs) and in a receiving stream upstream and downstream of a highway outfall. In this case study, SELDM version 1.0.1 (Granato, 2013a,b) was used to assess risks of adverse effects of runoff on receiving waters. Simulated total-copper concentrations were compared to water-quality aquatic-life criteria defined by the Massachusetts Department of Environmental Protection (2013) and the commonly used hardness based criteria (U.S. Environmental Protection Agency, 2014). These comparisons were made to assess the potential for adverse effects as defined by the risks for exceeding these criteria concentrations. Two sets of simulations were done to examine the highway-runoff contribution in relation to other potential sources:

- **Scenario 1, Low-development upstream-basin water quality:** This scenario was done to simulate the potential effect of highway runoff on the receiving-water quality if the upstream basin was largely undeveloped. In this scenario, total-copper concentrations were simulated by using suspended sediment concentrations, sediment-quality concentrations, and sediment-water distribution coefficients.
- **Scenario 2, Current conditions upstream-basin water quality:** This scenario was done to simulate the potential effect of highway runoff on the receiving-water quality if the upstream total-hardness and total-copper concentrations in stormwater represent a mixture of contributions from low-development and urban areas. This scenario, however, does not include other potential sources of sediment, total hardness, and total copper in the basin.

## **SIMULATION AREA**

In this study, the contributing area for the Charles River at Interstate 495 (I-495) in Bellingham Massachusetts (MA) is used to demonstrate methods for using the SELDM model. The latitude and longitude for this location is approximately 42.1071, and -71.4582, respectively. An 11.6

acre section of I-495 drains to the Charles River at this site. The on-line USGS StreamStats application (<http://water.usgs.gov/osw/streamstats/>) was used to delineate the upstream basin and obtain the drainage area. Table 1 contains the basin properties for the site of interest and upstream basin that were used to do three SELDM simulations. The basin slope and main channel length were calculated manually using methods described by Granato (2012; 2013a). In the low-development scenario (scenario 1), the upstream basin was simulated as if the total impervious area (TIA) was one percent and did not contain any directly-connected impervious area (DCIA). Two simulations were done for the current-conditions scenario (scenario 2). In the first simulation of scenario 2, the total of all Municipal Separate Storm Sewer System (MS4) areas in the basin (U.S. Environmental Protection Agency, 2015) were modeled as the site of interest. The remainder of the Charles River at I-495 was simulated as upstream of the aggregated MS4 area. The aggregate of the MS4 areas was simulated as one contributing area so the drainage area used in the MS4 simulation was the upstream basin minus the MS4 DCIA (Table 1). The upstream TIA in the MS4 simulation represents the remainder of TIA once the MS4 DCIA is removed. The combined stormflow concentrations from this simulation were used to calculate the upstream water-quality statistics that were used in the second (highway-runoff) simulation of scenario 2. The basin properties in the second simulation of scenario 2 represent current conditions with the undeveloped areas, the MS4 areas, and the other developed areas, which are scattered within the basin (Table 1).

**Table 1. Simulated drainage-basin characteristics of the highway, the directly-connected impervious areas, and the upstream basin for the Charles River at I-495 in Bellingham MA.**

[DCIA, directly connected impervious area; ft, feet; mi, miles; MS4, municipal separate storm sewer system; mi<sup>2</sup>, square miles; TIA, total impervious area; DCIA totals are from the U.S. Environmental Protection Agency (2015). Runoff coefficients and basin lag times are calculated by using TIA. Basin coordinates 42.1071 -71.4582.]

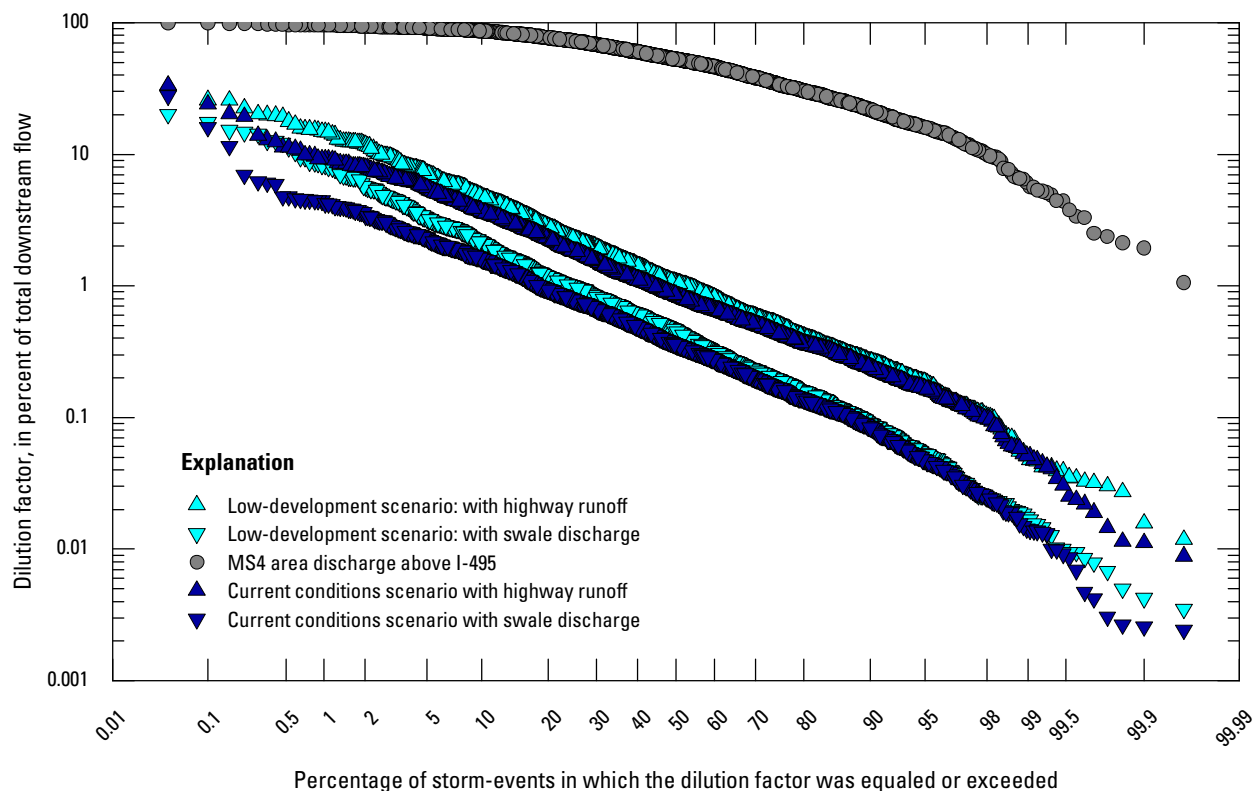
Simulated basin	Highway site or MS4 DCIA catchment area					
	Drainage area (acres)	Basin slope (ft/mi)	Channel length (ft)	TIA (percent)	Total DCIA (acres)	MS4 DCIA (acres)
Low development (scenario 1)	11.6	12	3,800	100	11.6	--
MS4 area scenario 2 step 1	1,118	12	2,500	100	1,118	1,118
Current conditions scenario 2 step 2	11.6	12	3,800	100	11.6	--
Simulated basin	Upstream basin					
	Drainage area (mi <sup>2</sup> )	Basin slope (ft/mi)	Channel length (ft)	TIA (percent)	Total DCIA (acres)	MS4 DCIA (acres)
Low development (scenario 1)	20.1	19.7	72,992	1	0	0
MS4 area scenario 2 step 1	18.35	19.7	72,992	8.7	311	0
Current conditions scenario 2 step 2	20.1	19.7	72,992	16.6	1,429	1,118

In both scenarios, the quality and quantity of flows from the highway and downstream of the highway are compared. The highway-runoff simulations represent a highway drainage design in which the runoff is collected from the pavement by drop inlets and conveyed directly to the stream through a trunk-line drainage system. The highway-swale simulations represent a commonly used highway-drainage design in which the runoff is routed through the swale before discharge to the receiving stream.

## **SIMULATED HYDROLOGY**

A 28-year simulation period that represents long-term hydrologic conditions in the area was used to conduct the water-quality simulations. SELDM uses Monte Carlo methods to generate a population of random events that are grouped into annual-load accounting years, but does not represent any particular time period or a particular time series (Granato 2013a). Precipitation, upstream pre-storm flows, runoff from the highway and the upstream basin, and flow modifications by the grassy swale were simulated by using standard methods described by Granato (2010; 2013a,b; 2014). Statistics for precipitation, pre-storm flow, and runoff coefficients from the FHWA 2010 dataset were used (Granato, 2010; 2013a,b). Precipitation was simulated by selecting long-term statistics from National Weather Service precipitation monitoring station 190575 in Bellingham, MA. Upstream pre-storm flows were simulated by selecting the average of statistics from four nearby streamgages with drainage areas and levels of development that are similar to the Charles River at I-495 in Bellingham, MA. These streamgages were 01108500 Wading River at West Mansfield, MA; 01105000 Neponset River at Norwood, MA; 01111300 Nipmuc River near Harrisville, RI; and 01105500 East Branch Neponset River at Canton, MA. Runoff coefficient statistics for the highway and upstream basins were calculated within SELDM by using the impervious fractions listed in table 1 (Granato, 2010; 2012; 2013a). The basin lag time for the highway was simulated by using the basin characteristics in table 1 and a basin development factor (BDF) of 12 (Granato, 2013a). The basin lag time for the MS4 area and upstream basin were calculated by the basin characteristics in table 1 and using the SELDM TIA option, a BDF of -1 (Granato, 2013a). The effects of the grassy swale on the volume and duration of runoff from the highway site were calculated by using the statistics for grassy swales reported by Granato (2014) with a maximum hydrograph-extension value of 1.83 hours for the swale.

The dilution factor graph (figure 1) is a summary of the effects of these hydrologic variables on simulation results. The dilution factor graph shows the percentage of concurrent downstream storm flows comprised of highway (or urban) runoff, which indicates the potential for water-quality exceedances caused by discharges from the site of interest. This graph shows that the highway runoff is a small proportion of concurrent downstream storm flows (less than 10 percent) for most storms in these simulations. Dilution factors for highway-swale discharge are lower than for highway-runoff discharges because the swale infiltrates runoff and extends the pavement-runoff hydrograph, which dilutes the discharge in a larger proportion of the upstream stormflow (Granato, 2014). The urban runoff from the large impervious MS4 areas, however, is a large part of the stormflows upstream of the highway in scenario 2. Comparison of the highway- and urban-runoff dilution factors indicates that the urban runoff may dominate water-quality in this basin under current conditions because it is a high proportion of total stormflow flow in many storm events. The highway and grassy-swale discharges are a smaller proportion of downstream flows in scenario 2 than in scenario 1 because the stormflow from the upstream basin with the urban areas is larger than the upstream stormflow from the less developed basin simulated in scenario 1.



**Figure 1. The stochastic population of downstream dilution factors for highway runoff, highway-swale discharges, and urban runoff from the aggregated municipal separate stormwater sewer system (MS4) areas upstream of the highway. The current-conditions scenario represents dilution factors for highway runoff and highway-swale discharges with upstream MS4 flows.**

### **SIMULATED HIGHWAY- AND URBAN-RUNOFF QUALITY**

SELDM uses statistics for the quality and quantity of highway-runoff and for stormwater BMP treatment variables to generate a stochastic population of flows, concentrations, and loads from the highway and BMP. Highway-runoff quality was simulated by using highway runoff data from local MA highways from version 1.0.0a of the highway-runoff database (Smith and Granato, 2010). The quality of runoff from the urban MS4 areas was simulated by using BMP influent data from the December 2014 version of the International BMP database ([www.bmpdatabase.org/](http://www.bmpdatabase.org/)) and data from sites in Boston, MA (Breault and others, 2002). Runoff quality was simulated as random variables by using the average, standard deviation, and skew of the logarithms of EMCs. In this study, the median for each of these statistical moments of the selected sites in each dataset was used as SELDM input to simulate highway- and urban runoff quality (Table 2). The quality of highway-swale discharge was calculated by using concentration-reduction statistics and the minimum irreducible concentration value for grassy swales defined by Granato (2014) to modify the concentrations of total copper in highway runoff. It was assumed that the swale did not modify total-hardness concentrations in highway runoff.

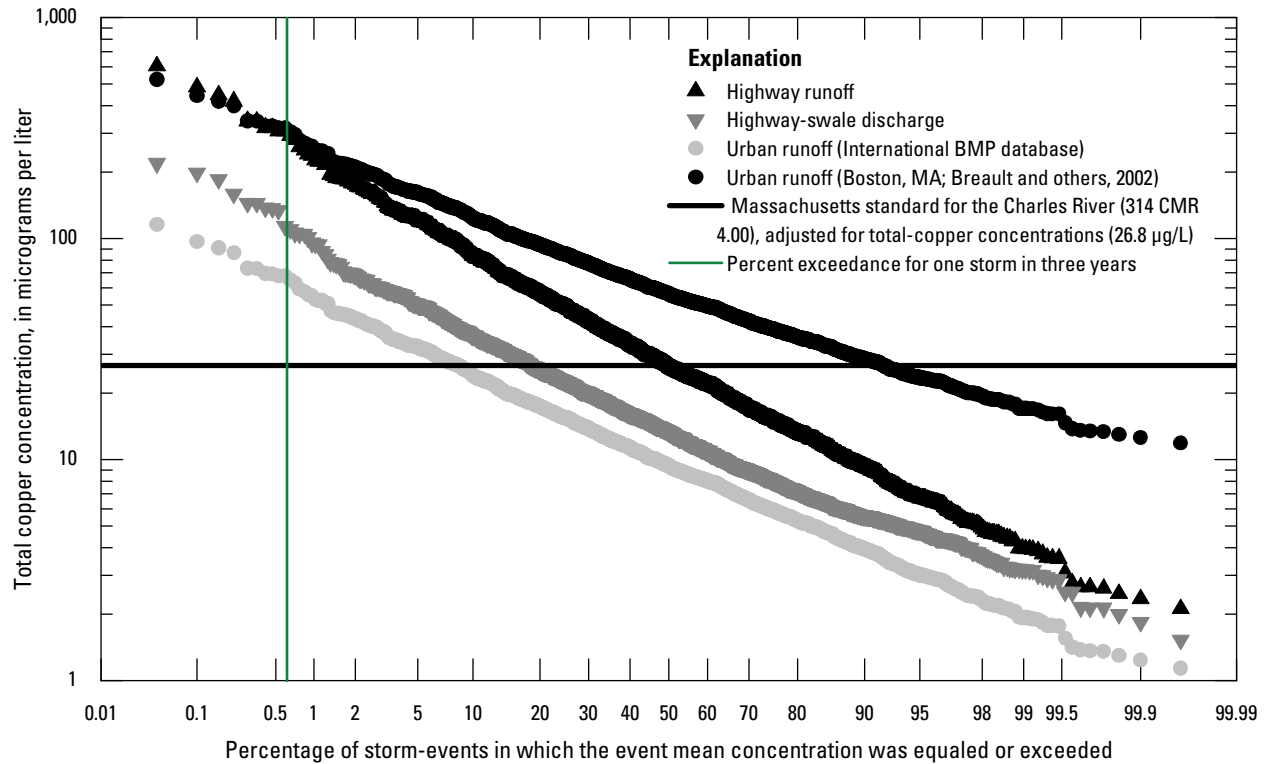
The resulting stochastic populations of total-copper EMCs for the 28-year simulation period are shown in figure 2. The simulated highway runoff and swale-discharge concentrations commonly are substantially lower than urban-runoff concentrations simulated by using statistics from sites in Boston, MA for most storm events. However, the simulated highway runoff and swale discharge concentrations commonly are substantially higher than urban-runoff concentrations simulated by using statistics from the international BMP database (Table 2). On average, simulated highway-runoff and swale-discharge concentrations are about 2.9 and 1.4 times the simulated International BMP database concentrations. Statistics from the international BMP database dataset rather than the Boston dataset (Breault and others, 2002) were used to simulate upstream sources of copper in scenario 2 as a conservative measure to assess potential adverse effects of highway runoff on water quality in the receiving stream.

**Table 2. Event-mean concentration statistics for total copper in highway- and urban-runoff.**

[ $\mu\text{g/L}$ , micrograms per liter; SD, standard deviation; Skew, coefficient of skewness, dimensionless. The median highway-site statistics are from sites on Interstates I-495, I-190, and State Route 2 from Smith and Granato (2010). The median urban-category statistics are from 40 commercial, 8 industrial, and 14 residential sites in the 2014 version of the international BMP database (<http://www.bmpdatabase.org/>). The median of Boston urban-category statistics are from the commercial (site 01104677), multifamily (site 01104673), and single-family (site 01104630) land use sites in Breault and others (2002).]

Site or land use statistics	Arithmetic			Logarithmic (base 10)		
	Average $\mu\text{g/L}$	SD $\mu\text{g/L}$	Skew	Average $\log(\mu\text{g/L})$	SD $\log(\mu\text{g/L})$	Skew
Median highway-site	37	30	1.18	1.43	0.376	0.150
Median of urban-category	11.3	6.87	1.38	0.975	0.308	0.114
Median of Boston urban-category	63	30	0.995	1.76	0.25	0.291

In figure 2, long-term simulation EMCs are shown with reference to the Massachusetts State receiving-water acute standard adjusted from the acute dissolved standard for total-copper concentrations in the Charles River (Massachusetts Department of Environmental Protection, 2013). This dissolved criterion of 25.7 micrograms per liter ( $\mu\text{g/L}$ ) is converted to the associated whole-water standard of 26.8  $\mu\text{g/L}$  by using the standard adjustment factor for copper of 0.96 (U.S. Environmental Protection Agency, 2014). These simulated concentrations also are shown with reference to the commonly used U.S. Environmental Protection Agency (2014) allowable exceedance risk for one-event in three years. The risk for a one-storm exceedance in three years is 0.58 percent based on the long-term average of 57 runoff-producing events per year in this simulation. About 92 percent of the urban runoff concentrations simulated with statistics from the Boston dataset equal or exceed the whole-water criterion. About 8 percent of the urban runoff concentrations simulated with statistics from the International BMP dataset equal or exceed this criterion. About 50 percent of highway-runoff concentrations and 18 percent of highway-swale discharge concentrations equal or exceed this criterion. Receiving water standards are not applicable to discharges, so this copper criterion for the Charles River is included in figure 2 for comparison to the results of upstream and downstream simulations, which are shown in subsequent figures in this report.



**Figure 2. Probability plot showing simulated event mean concentrations of total copper for highway-runoff, highway-swale discharge, and urban runoff.**

### **SIMULATED UPSTREAM AND DOWNSTREAM WATER QUALITY**

The two water-quality scenarios were designed to examine the potential risk for adverse effects of highway runoff or swale discharges from the I-495 site on the water quality of the Charles River downstream of the highway. The risks of adverse effects are assumed to equal the risk of exceeding the MA total-copper criterion of 26.8 µg/L in the receiving stream. However, simulations of total-hardness concentrations in the receiving waters indicate that a hardness-based criterion for total copper may be lower than the MA criterion for the Charles River. The average of 71 total-hardness concentrations measured in the Charles River at Dover (USGS station 01103500) was about 37.4 milligrams per liter (mg/L). Total-hardness concentrations tend to decrease with increasing streamflow (Granato and others, 2009; Risley and Granato, 2014), so a water-quality transport curve was developed to model total-hardness concentrations in stormflow. A water-quality transport curve is a relation between stormflow volumes and constituent concentrations (Granato, 2006; 2013a, Granato and others, 2009). Analysis of this data resulted in a two segment transport curve:

$$Hardness = 38.24 \times Stormflow^{-0.1132} \times 1.075^{K_{random}}, \quad (1)$$

if stormflow is less than 1.12 cubic feet per second per square mile (ft<sup>3</sup>/s/mi<sup>2</sup>) and

$$Hardness = 38.92 \times Stormflow^{-0.2678} \times 1.089^{K_{random}}, \quad (2)$$

if stormflow is greater than or equal to this threshold. The random variations around the transport curve are generated by using a standard-normal variate ( $K_{random}$ ). Both the rate of dilution and

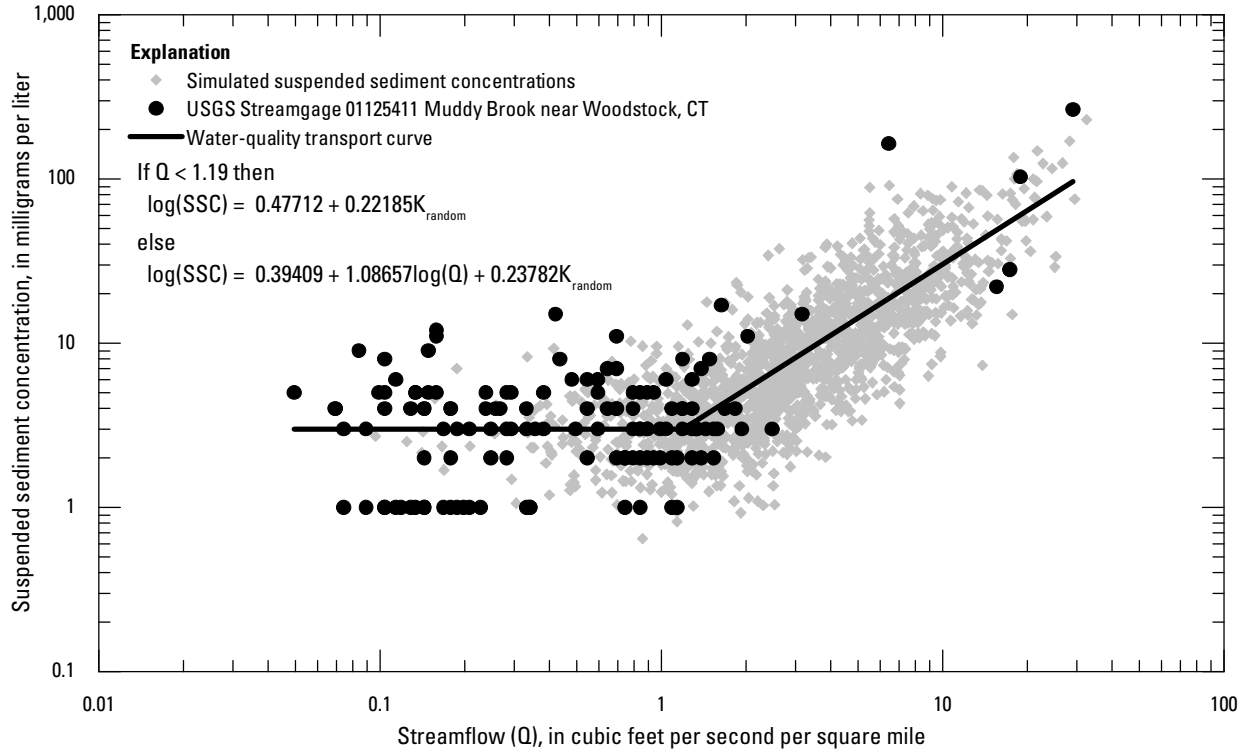
random variations in total-hardness concentrations increase above the  $1.12 \text{ ft}^3/\text{s}/\text{mi}^2$  threshold. The 28-year simulation using this two-segment transport curve results in an average upstream total-hardness concentration of 30.6 mg/L during storm events in scenario 1. If the average (1.18) and standard deviation (0.6325) of the logarithms of total hardness in highway runoff along I-495 are used to simulate runoff quality from the highways and the urban areas with a lognormal distribution, then the downstream total-hardness concentrations average 30.7 mg/L in scenario 1. On average, the associated hardness-based acute total-copper criterion would be 4.78  $\mu\text{g}/\text{L}$  upstream of the highway and the downstream criteria would be 4.79  $\mu\text{g}/\text{L}$  in scenario 1 based on the commonly used U.S. Environmental Protection Agency (2014) equations. The simulated upstream and downstream hardness concentrations were 35.46 and 35.54 mg/L in scenario 2. The associated upstream and downstream criteria would be 5.37 and 5.38  $\mu\text{g}/\text{L}$  of total copper in scenario 2.

**Scenario 1: Total-Copper Concentrations With Low Development.** A three-step process was used to provide estimates of total-copper concentrations upstream of the highway for the first water-quality scenario. In this low-development scenario it is assumed that geologic sources are a primary source of total copper. Therefore, the first step was to estimate suspended sediment concentrations (SSC), the second step was to estimate particulate copper concentrations, and the third step was to estimate total-copper concentrations.

A water-quality transport curve was developed to estimate SSC in the river. Data from USGS Streamgage 01125411 on the Muddy Brook near Woodstock, CT was used because 143 samples collected over a large range of flows were available, the basin is sparsely developed, and is comparable in size to the Charles River at I-495. Figure 3 shows the data, the two-segment water-quality transport curve, and a simulated population of SSC.

Bed-sediment copper concentration data compiled by Horowitz and Stephens (2008) was used to estimate the concentrations of particulate copper in the suspended sediment. Data from 14 samples collected in minimally-developed basins in New England, with population densities that were less than 60 people per square mile (equivalent to TIA value of about one percent), were used to estimate copper-concentration statistics for this simulation. The average particulate-copper concentration was 0.029  $\mu\text{g}$  of Cu per milligram (mg) of sediment. The average (-1.555) and standard deviation (0.1589) of the logarithms of these particulate copper concentrations were used to simulate particulate concentrations in the water column as a function of the simulated SSC (figure 4). The slope of the logarithm of particulate-copper concentration is one because it is calculated as the mass of copper per unit mass of sediment.

Estimates of the particulate-water distribution coefficients ( $K_d$ ), which are the ratios of particulate to dissolved metal, were needed to estimate the total-copper concentrations from SSC. Studies indicate that  $K_d$  values decrease as a function of increasing SSC because the proportion of fine-grained sediments with the greatest relative surface area decreases with increasing sediment concentrations (U.S. Environmental Protection Agency, 1985; Pelletier, 1996; Benoit and Rozan, 1999).



**Figure 3. Stochastic population of suspended sediment concentrations (SSC) in upstream flows (Q) calculated by using a transport curve developed with data from USGS streamgauge 01125411 Muddy Brook near Woodstock, CT and sediment concentrations simulated by using the transport curve with a population of random normal variates ( $K_{random}$ ).**

The logarithmic slopes and intercepts of the  $K_d$  equation calculated from the Pelletier's (1996) copper equation were selected because these coefficients represent the median of the three equations. Monte Carlo methods were used to estimate the median absolute deviation from the logarithmic  $SSC$ - $K_d$  regression line that would represent the random variations ( $K_{random}$ ) in estimated  $K_d$  values represented by the R-squared values for the  $K_d$  equations from the literature. The resulting equation is:

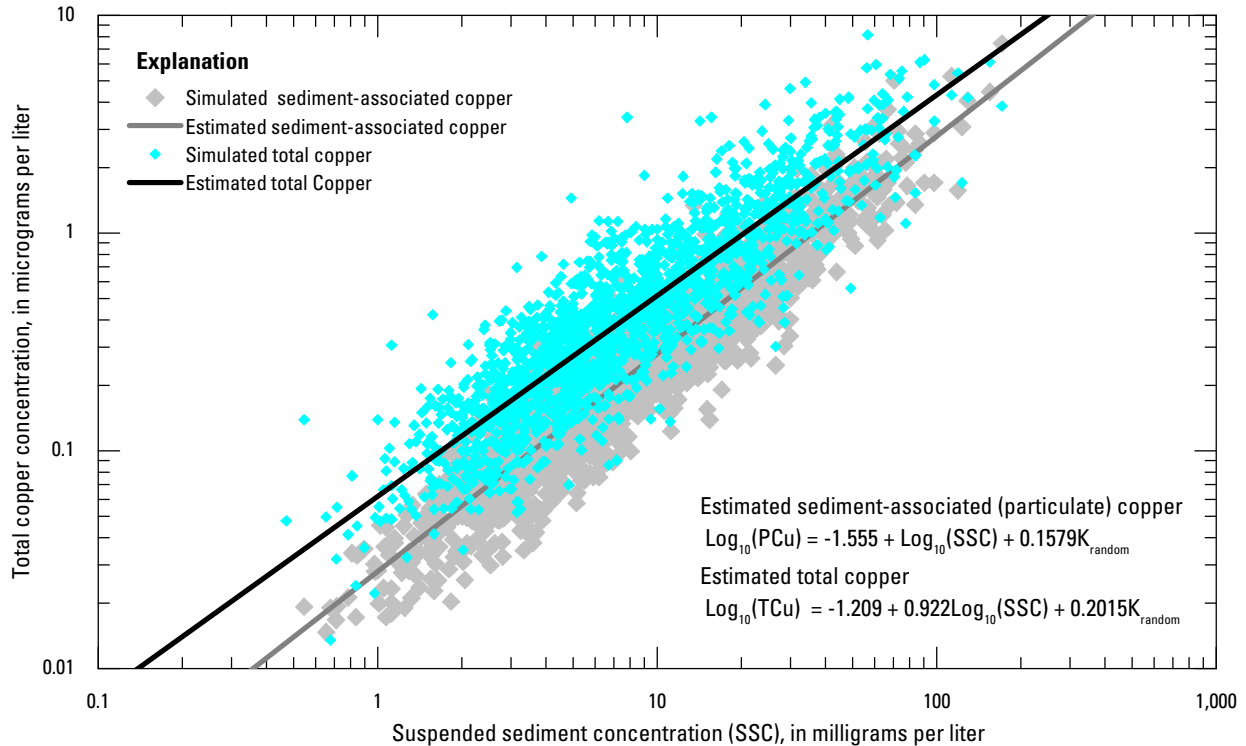
$$K_d = 577,068 \times SSC^{-0.617} \times 1.77^{K_{random}} \quad (3)$$

Once the  $K_d$  is estimated, the theoretical relation between the particulate copper ( $C_p$ ) and total copper ( $C_{Total}$ ) concentrations is:

$$C_{Total} = C_p \times \left( 1 + \frac{10^6}{K_d \cdot SSC} \right) \quad (4)$$

If  $C_p$  and  $K_d$  are functions of  $SSC$ , then  $C_{Total}$  also can be expressed as a function of  $SSC$  by substituting in the logarithmic regression equations:

$$C_{Total} = C_p \text{Intercept} \times SSC^{C_p \text{Slope}} \times \left( 1 + \frac{10^6}{K_d \text{Intercept} \times SSC^{(K_p \text{Slope} + 1)}} \right) \quad (5)$$



**Figure 4. Relationships between suspended sediment concentration and copper concentrations developed by using data from the literature and results of Monte Carlo simulations.**

This relation is made more complex knowing that  $SSC$ ,  $C_p$ , and  $K_d$  are stochastic variables with deterministic and random components. SELDM can model the  $SSC$  transport curve and dependent relations between  $SSC$  and  $C_p$ , and  $C_{Total}$  directly, but does not include a method to represent the relation as formulated in equation 5. Therefore Monte Carlo methods were used to simulate  $C_{Total}$  as a dependent variable from  $SSC$ ,  $C_p$ , and  $K_d$  outside of SELDM. A logarithmic regression relation with random variation was developed from the simulated data to model total copper as a dependent variable of  $SSC$ . This relation is shown in figure 4. The slope of the equation to predict  $C_p$  from  $SSC$  is one because the geometric mean concentration of copper in sediment is assumed to be constant with increasing sediment concentration. However, the slope of the equation to predict  $C_{Total}$  from  $SSC$  is 0.922, which represents the effect of the decrease in  $K_d$  with increasing sediment concentrations. This means that a calculated  $C_p$  value would exceed the associated  $C_{Total}$  if the  $SSC$  value is about 27,000 mg/L; a value that is about two orders of magnitude greater than the maximum simulated  $SSC$  value in this area based on available data. Available data indicates that the probability of equaling or exceeding 27,000 mg/L is less than  $10^{-15}$  percent in this area. As expected, the random variability of the total copper is greater than the random variability of the particulate copper because variability in the total copper values is associated with variability in particulate copper values and the variability in  $K_d$ , which is a function of the many geochemical interactions that determine the distribution of copper in any given storm event. The resulting upstream concentrations from this low-development scenario may be considered to be background concentrations upon which copper from other sources may be superimposed.

The results of this low-development scenario are shown in figure 5. During the 28-year simulation period, total-copper EMC values ranged from about 0.02 to 13  $\mu\text{g/L}$  upstream of the highway, 0.06 to 45  $\mu\text{g/L}$  downstream with highway runoff, and 0.03 to 13  $\mu\text{g/L}$  downstream with the highway-swale discharge. On average, the highway-runoff and highway-swale discharge increase the upstream concentrations by a factor of 2.14 and 1.25 in this low-development scenario. Only one event in 28 years exceeded the 26.8  $\mu\text{g/L}$  criterion (a risk of 0.062 percent) in the highway-runoff simulation, which is well below the commonly used one-event in three-year standard (a risk of 0.58 percent). The highway-swale simulation indicates that use of a simple grassy swale is sufficient to reduce all downstream concentrations below the 26.8  $\mu\text{g/L}$  total-copper criterion. If the hardness-based criterion for this scenario is used, however, then the percentages of exceedances would be about 0.75 percent of events upstream of the highway, 3.92 percent downstream of the highway with highway runoff and 0.87 percent with swale discharges. Thus the simulated natural background total-copper concentrations would exceed the hardness-based copper criterion much more frequently than the commonly used once in three year allowable exceedance risk criterion. Highway runoff would substantially increase the percentage of exceedances, but use of a simple grassy swale rather than a storm-drain conveyance system would reduce the risk of exceedance almost to the background concentrations.

**Scenario 2: Current Conditions.** A two-step process was used to provide estimates of total-copper concentrations in the current-conditions scenario. The first step was to model the 1,118 acres of directly-connected impervious area within MS4 areas in Bellingham, Hopkinton, Mendon, and Milford, MA as a single discharge to the receiving stream with upstream basin properties that represent the remainder of the basin upstream of the highway-discharge point (table 1). This simulation used the total-copper concentration equations developed in scenario 1 to represent upstream stormflow quality from the low-development areas. The median of urban-category statistics from the international BMP database (table 2) were used to represent runoff quality from the MS4 areas (figure 2). This Monte Carlo simulation indicates that the combined upstream and MS4 concentrations are in effect random. The urban inputs obscure the relations between stormflow, sediment, and copper because the DCIA area is large, the selected urban-runoff concentrations are much greater than upstream copper concentrations, and the urban-runoff concentrations are random. The second step was to use the concentrations downstream of the MS4 areas as upstream concentrations for the highway and highway-swale simulation.

The results of these simulations are shown in figure 5. During the 28-year simulation period, the range of upstream total-copper EMC values with the MS4 contributions was about 0.53 to 62.7  $\mu\text{g/L}$  and the average was 7.06  $\mu\text{g/L}$ . The range of downstream concentrations with highway runoff was 0.57 to 62  $\mu\text{g/L}$  and the average was 7.55  $\mu\text{g/L}$ . The range of downstream concentrations with highway-swale discharge was 0.54 to 62.4  $\mu\text{g/L}$  and the average was 7.14  $\mu\text{g/L}$ . On average, the MS4 contributions increase the copper concentrations upstream of the highway by more than an order of magnitude (about 17 times) in comparison to the upstream concentrations in the low-development scenario. In comparison, the highway runoff and swale discharge only increase the upstream concentrations by a factor of 1.07 and 1.01 on average in this current-conditions scenario. Upstream copper EMCs and downstream EMCs with grassy-swale discharge exceed the 26.8  $\mu\text{g/L}$  criterion in about 2.24 percent of storm events (36 events), and downstream EMCs with highway runoff exceed the criterion in about 2.3 percent of storm events (37 events). If the hardness-based criterion for this scenario (5.4  $\mu\text{g/L}$ ) is used, then the percentages of exceedances would be 46.6 percent of events upstream of the highway, 51.9

percent with highway runoff, and 47.2 percent with highway-swale discharges. These percentages are about two orders of magnitude greater than the commonly used once in three year allowable exceedance risk criterion. The additional effect of the highway runoff or swale discharge, however, is negligible in this scenario because the MS4 runoff has a much larger effect on upstream water quality in comparison to the low-development scenario and the highway contributing area at the crossing is only about 1 percent of the upstream MS4 DCIA (Table 1).

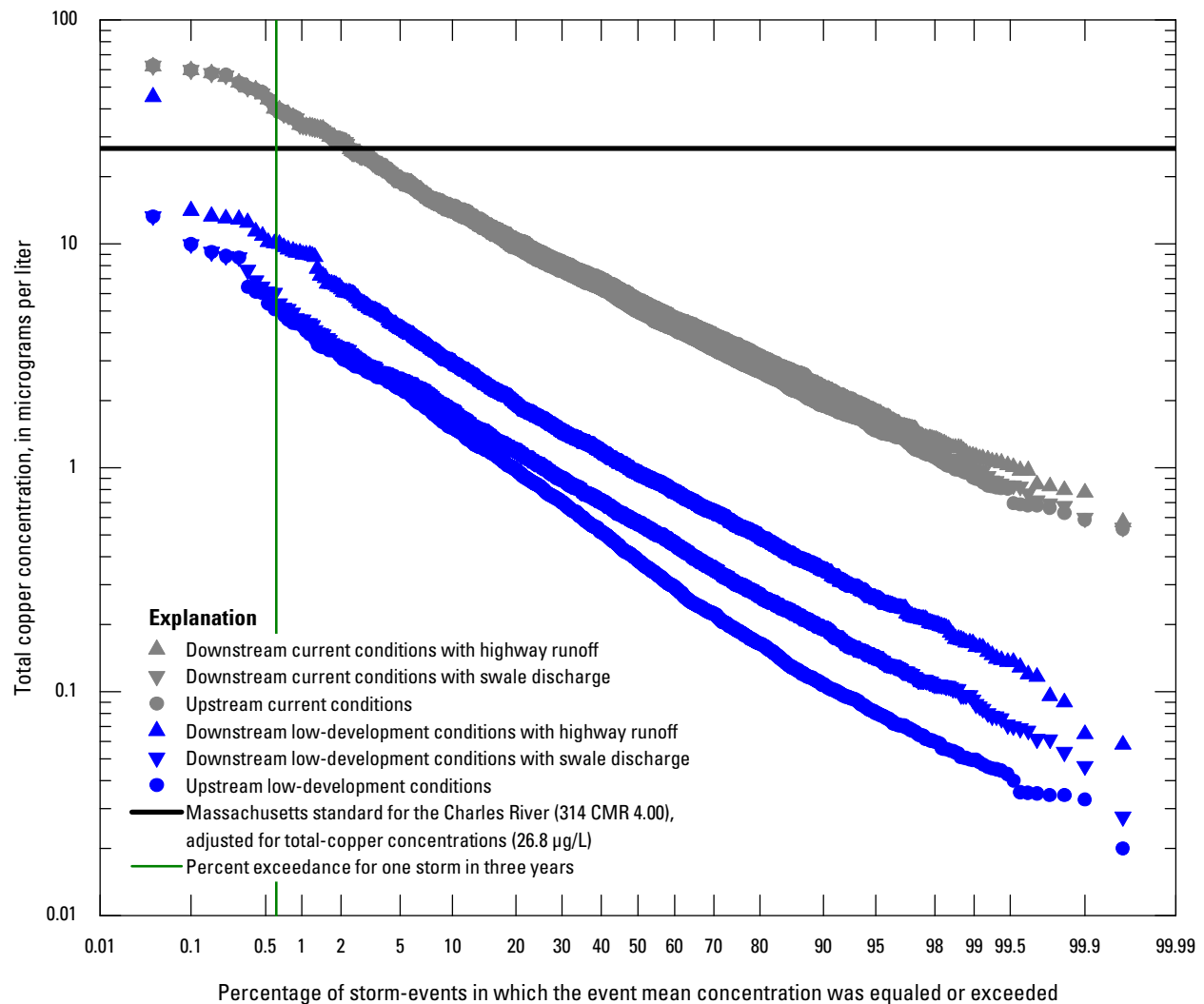


Figure 5. Probability plot showing simulated event mean concentrations upstream of the highway and downstream of the highway in the low-development and current-conditions scenarios.

Available total-copper EMC data for the Charles River (Breault and others, 2002) indicate the efficacy of these simulation methods. The geometric mean of simulated total-copper concentrations in upstream stormflows (5.15 µg/L), downstream stormflows with highway runoff (5.72 µg/L), and downstream stormflows with highway-swale discharge (5.28 µg/L) that were simulated for the Charles River, Bellingham site all are within the 95-percent confidence interval (4.85 to 6.91 µg/L) of the geometric mean (5.79 µg/L) of 10 EMC samples from USGS

monitoring station 01104615, on the Charles River at Watertown, MA. Although the drainage area at station 01104615 is about 10 times the drainage area at the site of interest, the land cover percentages at both sites are similar. The percentage of forest is 43.5 at Watertown versus 45.1 at Bellingham. The percentage of developed areas is 46.8 versus 46.4. The percentage of total impervious area is 17.8 versus 20. The percentages of other land-cover categories also are very similar.

## **SUMMARY AND CONCLUSIONS**

Decisionmakers need information about random variations in the quantity and quality of highway runoff, urban runoff, and upstream stormflows for estimating the potential effects of runoff on receiving waters downstream of a runoff discharge point. Although trace metals, including copper, are of primary concern for evaluating the potential effects of stormwater on receiving streams, reliable data for concentrations of trace metals in receiving streams during stormflow events are not commonly available. Therefore, methods for simulating trace metals in runoff and receiving waters are needed to assess risk for water-quality exceedance and the potential effectiveness of mitigation measures to reduce those risks.

In this study, the version 1.0.1 of the Stochastic Empirical Loading and Dilution Model (SELDM) was used to demonstrate methods for estimating event mean concentrations (EMCs) of trace metals in receiving waters where robust datasets are not available. These simulations also were done to examine the potential effects of highway runoff and highway-swale discharges on the risk for water-quality exceedances in a basin with a low-development and a current-conditions scenario. The hypothetical simulations were done by using properties of the Charles River basin above Interstate 495 (I-495) in Bellingham, Massachusetts (MA). This basin has a drainage area of 20.1 square miles and is 16.6 percent impervious. The 1,118 acres of directly connected impervious areas (DCIA) within the municipal separate storm sewer system (MS4) areas of four towns in the simulated basin are 52 percent of the TIA in the simulated basin in the current-conditions scenario. In both scenarios, an 11-acre section of I-495 drains to the Charles River at this site.

The hydrology and water quality of this site were simulated with SELDM by using data from nearby, hydrologically similar sites. Stormflow, total-hardness, suspended-sediment, and total-copper concentrations were simulated to assess risks for exceeding water-quality criteria for total copper. Total-hardness and suspended-sediment concentrations from low-development areas were simulated by using water-quality transport curves, which are relations between stormflow volumes and constituent concentrations, with random variation. Total-copper concentrations from low-development areas were simulated by using simulated sediment concentrations, concentrations of copper in streambed sediments, and particulate-water distribution coefficients. Concentrations of total hardness and total copper from the highway and urban areas were simulated by generating a population of random values from sample statistics. The simulated effects of the grassy swale on stormflows and concentrations in highway runoff were simulated by using published SELDM BMP-treatment statistics. Comparison of the simulated total-copper concentrations from the current-conditions scenario with EMC data collected at a downstream monitoring site indicates that the simulated geometric mean copper concentrations are within the 95-percent confidence interval of the geometric mean of the measured EMCs.

Results of the low-development and current-conditions scenarios indicate that neither highway runoff nor grassy swale discharge substantially change the risks for exceeding a MA whole-water criterion concentration of 26.8  $\mu\text{g/L}$  for total copper in the Charles River. In the low-development scenario none of the upstream EMCs exceeded this MA whole water criterion.

Only one highway-runoff EMC in the 28 year simulation exceeded the MA criterion and use of a simple grassy swale eliminated this exceedance. In the second (current-conditions) scenario, urban runoff from the upstream MS4 areas increased the percentage of exceedances to 2.24 percent (36 events in 28 years), which exceeds the commonly used once in three-year allowable exceedance risk criterion of 0.58 percent allowable exceedances. The percent exceedance downstream of the highway was 2.3 percent (37 events in 28 years) with highway runoff and 2.24 percent with swale discharge.

If the simulated total-hardness values are used to calculate a hardness-based criterion for copper with the commonly used U.S. Environmental Agency (USEPA) hardness-based criterion, then this criterion would be about 5 µg/L. In the low-development scenario total-copper EMCs upstream of the highway would exceed this hardness-based criterion in about 0.68 percent of events upstream of the highway, 3.55 percent with highway runoff and 0.81 percent with swale discharges. Thus, the upstream exceedances would occur about 1.17 times more often than the allowable one event in three year exceedance frequency, even though the upstream copper concentrations are based on sediment quality from undeveloped areas. If the hardness-based criterion (5.4 µg/L) is used for the current-conditions scenario, then the percentages of exceedances would be 46.6 percent of events upstream of the highway, 51.9 percent with highway runoff, and 47.2 percent with swale discharges. In this scenario, runoff from the large MS4 areas upstream of the highway dominates the water quality at this site of interest.

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