Prepared in cooperation with the Oregon Department of Transportation

# Assessing Potential Effects of Highway and Urban Runoff on Receiving Streams in Total Maximum Daily Load Watersheds in Oregon Using the Stochastic Empirical Loading and Dilution Model

Scientific Investigations Report 2019-5053

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

**Cover:** Mill Creek looking upstream from Mill Creek Road upstream of Turner, Oregon.
Photograph by Adam Stonewall, U.S. Geological Survey, May 4, 2019.

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DAVID BERNHARDT, Secretary

**U.S. Geological Survey**
James F. Reilly II, Director

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## Figures—Continued

## Figures—Continued

## Figures—Continued

## Figures—Continued



## Tables

## Tables—Continued

# Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 0.004047 | square kilometer ($km^2$) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| | Flow rate | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| cubic foot per second per square mile ($[ft^3/s]/mi^2$) | 0.01093 | cubic meter per second per square kilometer ($[m^3/s]/km^2$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| | Mass | |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |
| ton, short (2,000 lb) | 0.9072 | metric ton (t) |

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| meter (m) | 1.094 | yard (yd) |

# Datum

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

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

# Supplemental Information

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

# Abbreviations

| | |
|---|---|
| BLM | Biotic Ligand Model |
| BMP | best-management practice |
| CMC | Criteria Maximum Concentration |
| Cu | copper |
| DCu | dissolved copper |
| EMC | event mean concentration |
| FHWA | Federal Highway Administration |
| USEPA | U.S. Environmental Protection Agency |
| GIS | geographic information system |
| HRDB | Highway-Runoff Database |
| HRF | hydrograph recession factor |
| I-5 | Interstate 5 |
| MIC | minimum irreducible concentration |
| MOVE.1 | maintenance of variance type 1 |
| MPV | most probable value |
| NPDES MS4 | National Pollutant Discharge Elimination System Municipal Separate Storm Sewer System |
| ODEQ | Oregon Department of Environmental Quality |
| ODOT | Oregon Department of Transportation |
| PCu | particulate copper |
| $R^2$ | coefficient of determination |
| SD | standard deviation |
| SELDM | Stochastic Empirical Loading and Dilution Model |
| SS | suspended sediment |
| SSC | suspended sediment concentration |
| SSL | suspended sediment load |
| TCu | total copper |
| TIA | total impervious area |
| TMDL | Total Maximum Daily Load |
| TP | total phosphorus |
| TSS | total suspended solids |
| USGS | U.S. Geological Survey |

# Assessing Potential Effects of Highway and Urban Runoff on Receiving Streams in Total Maximum Daily Load Watersheds in Oregon Using the Stochastic Empirical Loading and Dilution Model

By Adam J. Stonewall[1], Gregory E. Granato[2], and Kira M. Glover-Cutter[3]

## Abstract

The Stochastic Empirical Loading and Dilution Model (SELDM) was developed by the U.S. Geological Survey (USGS) in cooperation with the Federal Highway Administration to simulate stormwater quality. To assess the effects of runoff, SELDM uses a stochastic mass-balance approach to estimate combinations of pre-storm streamflow, stormflow, highway runoff, event mean concentrations (EMCs) and stormwater constituent loads from a site of interest. In addition, SELDM can be used to assess the effects of stormwater Best Management Practices (BMPs), which are designed to mitigate the adverse effects of runoff into a waterbody.

Adverse effects of stormwater on receiving waters are one of the greatest unsolved water-quality problems Nationwide. State DOTs, municipalities, Federal facilities, and private property owners who manage impervious surfaces need information about the potential magnitude of their contributions and the potential effectiveness of methods to mitigate the adverse effects of runoff. Because the efficacy of at-site controls are limited, information about the potential effectiveness of alternative strategies is needed.

The USGS, in cooperation with the Oregon Department of Transportation (ODOT), conducted a study to research methods in which SELDM can be used to enhance the efficiency of ODOT's stormwater program, support the development of a stormwater banking program, and meet environmental goals. Results can be used to develop a strategic, systems-level approach to stormwater management by considering entire watersheds instead of individual road crossings. Two watersheds, Bear Creek and Mill Creek, in western Oregon were selected for analysis. Within each watershed, seven road crossings were selected for demonstrating the utility of SELDM in nested basins.

Precipitation statistics, pre-storm streamflow, runoff coefficients, and hydrograph recession factors were calculated for each location and used in SELDM to simulate flow, water-quality concentrations, and constituent loads in the upstream basin, from the highway (or developed area), and downstream from the road crossing. Three water-quality constituents were selected for modeling: suspended-sediment concentration (SSC), total phosphorus (TP), and total copper (TCu). Using water-quality transport curves, the relations between streamflow and SSC and between streamflow and TP were simulated. Concentrations of TCu were simulated by configuring a linear relation between SSC and TCu. A generic BMP was simulated using the median treatment statistics for flow reductions, hydrograph extensions, concentration reductions, and minimum irreducible concentrations from nine BMP categories with data from the 2012 International BMP database.

Five simulation scenarios were modeled for demonstrative purposes. These simulations were used to evaluate potential effects of different watershed properties, water-quality inputs, and stormwater mitigation measures. Instream EMCs were compared to hypothetical water-quality criteria for suspended sediment, total phosphorus, and total copper to demonstrate the concept of water-quality risk analysis. For all five scenarios, it was assumed that highway-runoff concentrations were independent of location or average annual daily traffic. These five scenarios are as follows:

- Simulation Scenario 1—Natural Conditions (hereafter Simulation Scenario 1) represents conditions in an undeveloped watershed. This scenario demonstrates that the strategic placement of a hypothetical road crossing within a watershed could be used to avoid exceeding water-quality standards of TP and SSC, but that no location choice results in meeting TCu standards. Implementation of BMP had the most pronounced effects on downstream water-quality constituent EMCs at road crossings with the highest ratio of highway catchment area to upstream drainage area, but the largest effect of BMP treatment on mean annual load is based on highway catchment area alone.

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[2] USGS New England Water Science Center

[3] Oregon Department of Transportation

- Simulation Scenario 2—Current Conditions (hereafter Simulation Scenario 2) represents current watershed conditions, where all developed area upstream from the road crossing was modeled as a highway and combined with the undeveloped part of the upstream drainage area (scenario 2A) and where the output from scenario 2A is used for the upstream area (developed area and the undeveloped area), and where the road crossing is added as usual (scenario 2B). Scenario 2 results indicate that attaining water-quality standards is more difficult with upstream developed areas. Specific road-crossing sites can be selected to achieve the fewest water-quality exceedances per year, but water-quality targets are not met without BMP implementation, and in some instances are not achievable even with BMP implementation. Results from this scenario also serve to quantify the upper limit of constituent reduction if funding were available to implement BMPs to large areas of development, and to quantify how much area would need BMP implementation to achieve water-quality targets.

- Simulation Scenario 3—Alternative Road Layouts (hereafter Simulation Scenario 3) was designed to assess the sensitivity of SELDM to various road layouts. In this scenario, different highway configurations were superimposed at one road crossing. Results indicate that downstream water-quality constituent EMCs did not exhibit much variation, but annual water-quality constituent loads varied considerably.

- Simulation Scenario 4—Varying Road Width (hereafter Simulation Scenario 4) was designed to assess the sensitivity of SELDM to road width. Similar to scenario 3, the results indicate little variation in downstream water-quality constituent EMCs, but annual water-quality constituent loads increased in proportion to road width.

- Simulation scenario 5—Changes to Impervious Area (hereafter Simulation Scenario 5) was designed to investigate the effects of changing amounts of imperviousness upstream from the road crossing. Results indicate that the downstream water-quality constituent EMCs are highly correlated with the percentage of impervious area upstream.

# Introduction

Stormwater runoff from all types of land use, including commercial areas, industrial areas, residential areas, roads, highways, agriculture, rangelands, and even forested areas, increase concentrations and loads of water-quality constituents such as nutrients, sediment, and metals in receiving waters (Maestre and Pitt, 2005; Washington State Department of Ecology, 2011; Clary and Leisenring, 2015). Stormwater mitigation measures, commonly known as structural best management practices (BMPs), are costly to build and maintain. For example, Taylor and others (2014) estimated long-term life-cycle costs for removing a pound of sediment, phosphorus, or copper by using conventional stormwater BMPs were, on average [in U.S. dollars ($)], about $9.32, $5,111, or $38,488, respectively. Municipal and State governments have limited resources for implementing such stormwater mitigation measures, and decision makers need tools, techniques, and information to maximize potential environmental benefits with available resources.

There is increasing pressure on the Oregon Department of Transportation (ODOT) stormwater treatment program from existing and future permitting requirements from the Endangered Species Act and the Clean Water Act, including a possible requirement to implement a stormwater treatment retrofit program in the forthcoming updated National Pollutant Discharge Elimination System Municipal Separate Storm Sewer System (NPDES MS4) permit. Currently, ODOT stormwater treatment facilities at highway sites are implemented at a project level, without consideration of broader transportation system needs, regional environmental benefits, or additive maintenance burdens. To address these permitting and planning concerns for stormwater treatment and facility placement, strategies are needed for assessing the effect of highways on water quality within a watershed.

A mitigation bank is a wetland, stream, or other aquatic resource area that has been restored, established, enhanced, or (in certain circumstances) preserved for the purpose of providing compensation for unavoidable effects to aquatic resources permitted under Section 404 of the Clean Water Act or a similar State or local wetland regulation. Mitigation banking can optimize environmental benefit by strategically focusing on large, substantial efforts, thus reducing mitigation costs through economy of scale, and results in a temporal gain by providing the benefit in advance of the adverse effect.

The ODOT controls only a narrow right-of-way that crosses multiple watersheds and water bodies and consequently has limited opportunities for mitigating potential effects of highway runoff (Oregon Department of Environmental Quality and Oregon Department of Transportation, 2011). Stormwater treatment banks, which are stormwater control measure BMPs constructed by ODOT for stakeholders, can be used to offset lack of complete treatment on projects because of constraints or low cost-effectiveness. Placement of stormwater treatment banks requires analysis to determine the level of benefit to the watershed and to identify locations where the bank would provide a high level of benefit. Strategic planning can then reduce the reliance on project-by-project stormwater management and support a functional retrofit program by identifying and focusing on areas where transportation and environmental priorities coincide. The result can be fewer, larger, well-placed BMPs instead of multiple scattered, small, maintenance-intensive BMPs. Watershed level analysis could also ensure that ODOT responsibilities related to highway runoff, such as Total Maximum Daily Load (TMDL) allocation and Superfund (USEPA, 2019a; ODEQ, 2019) and Sediment Cleanup (USEPA, 2019b), are based on an accurate assessment of potential adverse effects of highway runoff.

Implementing a stormwater banking strategy requires a watershed-wide understanding of potential effects of highway runoff on receiving streams. The effect of the ODOT highway system on receiving-water quality is poorly understood, and research is needed to collect data and develop protocols for evaluating how the absolute and relative contribution of highway runoff to stream water quality changes throughout a watershed.

The U.S. Geological Survey (USGS), in cooperation with the Federal Highway Administration (FHWA), developed the Stochastic Empirical Loading and Dilution Model (SELDM) to provide information needed for managing highway stormwater flows, loads, and concentrations to minimize potential effects of runoff on receiving waters. SELDM uses a Monte Carlo method to estimate combinations of flows, concentrations, and loads of runoff constituents from a site of interest and its upstream basin to estimate the risk that stormwater runoff may have adverse effects on the water quality of receiving streams (Granato, 2006, 2008, 2010, 2016; Granato and Cazenas, 2009; Granato and others, 2009). Although SELDM was developed as a highway-runoff model, it is a lumped parameter model that can be used to simulate the quantity and quality of runoff from any land use (Granato and Jones, 2016; Stonewall and others, 2018) . SELDM can be used to estimate the risk of downstream water-quality exceedances resulting from stormwater runoff using scenario simulations and sensitivity analyses.

The USGS, in cooperation with the Oregon Department of Transportation (ODOT), conducted a study to research methods in which SELDM can be used to enhance the efficiency of ODOT's stormwater program, support the development of a stormwater banking program, and meet environmental goals. The purpose of this cooperative study is to assess potential effects of highway and urban runoff on receiving streams in TMDL watersheds in Oregon using SELDM. Two watersheds, Bear Creek and Mill Creek, in western Oregon were selected for analysis. Within each watershed, seven road crossings were selected for demonstrating the utility of SELDM in nested watersheds. Three water-quality constituents were selected for modeling: suspended-sediment concentration (SSC), total phosphorus (TP), and total copper (TCu).

In a previous study, SELDM was used to simulate streamflow and hypothetical constituent loadings and concentrations at six western Oregon highway study sites (Risley and Granato, 2014). The upstream basins of the sites ranged from 0.16 to 6.56 square miles ($mi^2$). Although two of the study sites were in nested watersheds (the sites were within the same watershed), the other four sites were in separate watersheds. Unlike Risley and Granato (2014), in this study SELDM was used to simulate water quality at multiple locations within a watershed. In watersheds where ODOT has more than a single road crossing, the contribution of ODOT stormwater to the watershed constituent load is complicated and not always well understood. ODOT efforts to meet TMDL obligations in watersheds with multiple crossings could be inefficient and less cost effective than necessary. By developing appropriate protocols and procedures, SELDM watershed analysis could then be used to identify sites within a watershed with the greatest overall environmental benefit for treating highway runoff.

The primary objectives of this study included the following:

1. Develop and demonstrate techniques for geographic analysis that use the roadway and land use/land cover information in StreamStats (U.S. Geological Survey, 2018) to apply SELDM at selected points in the watershed. These techniques include manual and batch-processing techniques that can be used to model contributions of flows, concentrations, and loads in stormwater from highway sites and other upstream land uses. These techniques enable mass-balance analyses in selected watersheds with SELDM based on the land use/cover percentages upstream from any selected highway site.

2. Demonstrate methods for using SELDM with statistics on the quantity and quality of runoff from highways and other land uses and with BMP treatment statistics to simulate the cumulative effects of runoff from different areas in a watershed. These techniques can be used by ODOT and others to help identify mitigation measures to maximize benefits, while minimizing potential effects of runoff on receiving streams within a watershed and minimizing costs for implementing stormwater BMPs.

## Purpose and Scope

This report describes an assessment of potential effects of highway and urban runoff on receiving streams in TMDL watersheds in Oregon using SELDM. Specifically, this report documents advanced level-two analysis techniques that can be used to develop refined planning-level estimates needed for robust decision making.

To support the primary study objectives, this report documents the results of the following tasks:

- Perform a geographic analysis of Oregon roadways and upstream land uses and land covers.
- Select two example Oregon watersheds for stormwater analysis.
- Compute and compile storm precipitation and hydrologic statistics.
- Compile runoff-quality data and statistics for simulating highway-runoff discharges.
- Compile runoff-quality data and statistics for simulating runoff discharges for non-highway land uses/land covers.
- Perform watershed-scale SELDM simulations.
- Simulate the potential effectiveness of stormwater mitigation methods for reducing the risks of water-quality exceedances.

The assessment described in this report can be used to develop a strategic, systems-level approach to stormwater management by considering entire watersheds instead of individual road crossings. The results can be used to potentially develop a formal stormwater-treatment banking program and retrofit program. Specifically, development of watershed-level analysis protocols with SELDM can be used to increase efficiency and reduce costs by (1) eliminating the time needed to find off-site treatment, (2) limiting or avoiding multiple small treatment facilities that have limited benefit and cumulatively place stress on available resources to maintain water-quality facilities, (3) providing a tool to set appropriate TMDL treatment requirements, (4) providing Environmental Impact Statements (EIS) with a quantitative analysis of cumulative impact, and (5) providing a tool available to meet NPDES MS4 requirements for stormwater retrofits and program effectiveness measures. Additionally, environmental goals may be supported by identifying high value treatment sites and strategies for vulnerable and high priority watersheds.

## Terminology

The following terminology, much of which is taken from Risley and Granato (2014), is used throughout this report:

***Highway runoff*** is the volume of runoff from the highway catchment area during a storm event.

***Highway catchment area*** is the area of a highway that drains into the stream of interest during a storm event.

***Concurrent upstream stormflow*** is the combined volume of upstream runoff (volume of runoff from the upstream basin, without prestorm streamflow, that occurs during the same time period as highway runoff during a storm event) and upstream prestorm streamflow during the same time period as highway runoff (or BMP discharge) during a storm event.

***Concurrent downstream stormflow*** is the combined volume of highway runoff and upstream stormflow during the same time period as highway runoff (or BMP discharge) during a storm event.

***Event mean concentration (EMC)*** refers to a flow-weighted mean concentration during a rainfall-runoff event. It is calculated by dividing the total pollutant load mass by the total runoff volume of the stream or highway under consideration. In this report, the term “concentration” is often used to encompass both EMCs and constituent concentrations in a more general sense.

***Nested watershed*** is a watershed located within a larger watershed. For example, the watershed for Emigrant Creek at Highway 66 is nested within the larger Bear Creek watershed.

***Road crossing*** is the point of intersection between the stream of interest and a road. It could be a bridge or a culvert. Each road crossing represents the downstream end of a nested watershed. The term can be considered synonymous with ”stream crossing, ” although the latter term was avoided for this report for consistency.

In statistics, the ***location*** is the central tendency of a statistical population. Common measures of location include the arithmetic mean, the median, the mode, and the interquartile mean.

In statistics, the ***population*** is the total membership or “population” of a defined class of people, objects, or events. For example, all total copper runoff concentrations from a specific highway would be considered a population of concentrations, as they share membership of being from the same physical location (a specific highway), and are of the same type of event (highway-runoff concentrations).

For the purposes of this study, ***exceedance*** is the act of exceeding a water-quality standard. Similarly, ***exceedance probability*** is the probability of exceeding a water-quality criterion for a given number of events or duration of time. In this study, ***exceedance probability*** will most commonly be used to denote the probability of exceeding a water-quality criterion for any storm event, unless denoted otherwise (for example, “annual exceedance probability”).

***Cumulative distribution function*** is an equation or series of data that indicate(s) the probability that a specific value will be equaled or exceeded. As a hypothetical example, a cumulative distribution function might show that at a specific location on Mill Creek, for any given precipitation event, the probability might be 10 percent that the downstream concentration of TP is equal to or greater than 0.1 milligram per liter (mg/L). At the same time, the probability at the same location might be 2 percent that the downstream concentration of TP is equal to or greater than 0.5 mg/L. Cumulative distribution functions are plotted regularly in this report for illustrative purposes.

The terms ***road*** and ***highway*** are used interchangeably in this report.

# SELDM Background

SELDM was developed to estimate the risk of exceeding of specific stormwater concentration, flow, and (or) constituent loading goals; to evaluate the need for mitigation measures; and to estimate the effectiveness of such measures for reducing these risks (Granato, 2013). SELDM is designed to provide long-term, planning-level estimates of constituent EMCs and loads. These estimates can be used to assess and evaluate alternative management scenarios. Planning-level estimates may commonly include large uncertainties (Barnwell and Krenkel, 1982; Marsalek, 1991; Granato, 2013). In particular, measured stormwater flows and EMCs can vary by several orders of magnitude, even within individual monitoring sites. The analyses selected for this study are intended to demonstrate some potential uses for SELDM in modeling such a large degree of uncertainty that would help inform decision-making for long-term planning. The simulation results can be used to estimate downstream water-quality constituent EMCs, provide an example concentration risk analysis, and produce estimates of long-term loads of suspended sediment (SS), TP, and TCu.

SELDM is designed to simulate the combinations of stormflow volume, EMCs, and loads from many variables to provide planning-level estimates of the combinations of these variables over a long time period (Granato, 2013). SELDM is also designed to provide for three general levels of analysis. In a level-one analysis, the user can select default regional input statistics (ecoregion or rain zone) available within SELDM to easily and rapidly develop a planning-level estimate to use as a screening tool. If the risks of adverse effects from runoff at the site of interest are sufficiently low, then the analyst and decision makers can conclude that there is no finding of significant effect and shift the focus of analysis and investment in mitigation measures to other sites that may have greater risks for adverse effects. If the risks for adverse effects at a site are in question after a level-one analysis or the site is of special interest, then the analyst can proceed to a level-two analysis. In a level-two analysis, regional estimates of input statistics are replaced with estimates developed by using data and information from nearby, hydrologically similar sites. SELDM supports generation of level-two estimates from nearby precipitation and streamflow monitoring sites by using statistics available within the model analyses. However, advanced analysis techniques can be used to further refine these level-two estimates (Stonewall, 2019). In most cases, because of the large variability in physical, chemical, and anthropogenic factors affecting stormwater quality, a level-two analysis is sufficient for informed decision making. At sites of special concern (for example, a site upstream from a water supply or habitat for an endangered species), a level-three analysis that uses robust datasets collected at the site of interest may be warranted. The level-three analysis is not the default approach because site-specific field monitoring efforts are resource intensive, and it can take years to collect enough data to substantially reduce the uncertainty of input variables. Additionally, in most cases data collected at a site of interest over a short period may not represent either the past or future conditions at that site.

# Geographic Analysis of State Roadways and Upstream Land Use and Land Cover

In 2015, the USGS, in cooperation with ODOT, developed state-wide Geographic Information System (GIS) data layers for roadways and selected land covers within Oregon. These data layers were added to the USGS StreamStats application for Oregon and are available for public use (U.S. Geological Survey, 2018). The data layers allow for the calculation of land use, land cover, total impervious percentage, the length of State and non-State roads, and other basin properties within basins delineated by the user with StreamStats throughout Oregon.

Using a batch process, all Oregon watersheds west of the Cascade mountain range were categorized according to specific intervals of drainage area that were deemed of interest (table 1). Watersheds were delineated using the NHDPlus (version 1) 30-meter (m) resolution elevation data (U.S. Environmental Protection Agency, 2006). Using the program ArcGIS (Esri, 2017), flow accumulation grids were created at a 30-m resolution and snapped to the elevation grid.

**Table 1.** Classification of watersheds of specific drainage areas in Oregon.

[**Abbreviation:** $mi^2$, square miles]

| Targeted watershed size(mi2) | Minimum watershed size (mi2) | Maximum watershed size (mi2) | Number of watersheds |
|---|---|---|---|
| 5 | 4.999 | 5.001 | 142 |
| 10 | 9.998 | 10.002 | 105 |
| 25 | 24.995 | 25.005 | 49 |
| 50 | 49.5 | 50.5 | 109 |
| 85 | 80 | 90 | 16 |
| 95 | 90 | 100 | 16 |
| 105 | 100 | 110 | 16 |
| 115 | 110 | 120 | 22 |
| 200 | 180 | 220 | 68 |

By grouping all potential watersheds into narrow bands of drainage area, these bands could be evaluated to calculate "typical" basin characteristics for watersheds of that size. Because there are 300,878 miles (mi) of streams with 87,551 mi of perennial streams in the National Hydrography Dataset for Oregon (U.S. Environmental Protection Agency, 2013b), one might expect that the number of delineated basins for the selected drainage area sizes would be much larger, but several factors influence the delineation process. From a physiographical perspective, the drainage area increases exponentially with increasing channel length. For example, Granato (2013) evaluated drainage area and main-channel length at 845 streamgages nationwide and determined that drainage area increased at a rate of 0.426 times the main channel length to the 1.74 power. Individual streamgages, however, varied from this regression line because additional drainage area is accumulated in blocks as the main channel crosses topographic crenulations (areas on a topographic map in which the contour lines appear to fold back against themselves) and tributary areas. Furthermore, the National Hydrography Dataset used in StreamStats is discretized to a 30-m grid, which accentuates the step changes in drainage area with increasing channel length. The discretized grid also explains the choice of narrow watershed area bands (tables 1-2) used in the analysis; if wider bands were used, then the same basin could be sampled twice or more as the GIS algorithm worked from cell to cell along each stream. Although the delineated basins represent the complete population of watersheds that exactly fit within the drainage-area bands, these watersheds should be viewed as a sample of similar-sized watersheds. For example, a watershed of drainage area 5.0008 $mi^2$ would be outside of the drainage area band and not be considered for this analysis. However, the difference in size between watersheds with drainage areas of 5.0008 and 5.0000 $mi^2$ would not be considered substantially different. Consequently, the narrow band used to limit the number of watersheds evaluated and prevent the duplicate selection of watersheds results in only a sample of what could be considered the same population of watersheds being evaluated. All watersheds were screened to eliminate specific conditions that were not appropriate for this analysis. Examples of these conditions include large areas of artificial canals and (or) storage such as reservoirs, lakes, or ponds.

The delineation bands for watersheds of drainage areas between 80 and 120 $mi^2$ were relaxed to include ranges of ±5 $mi^2$. This step was taken to include at least one example watershed with a drainage area in that range for further analysis. For these watersheds, nested watersheds within the drainage-area criteria on the same stream were not used to calculate basin characteristic statistics; one representative watershed closest to the nominal drainage area was selected.

Selected basin characteristics (table 2) for targeted watersheds (table 1) were calculated using the StreamStats batch processor. Basin characteristics that were surmised to have an influence on streamflow, road density, road usage, and (or) water-quality contaminant levels were included for further analysis (table 2, basin characteristics). Basin characteristics surmised to have little or no influence were excluded from further analysis. ArcGIS was also used to count the number of major, minor, and State road crossings for each watershed.

## Selection of Watersheds for Stormwater Analyses

The following criteria were used to select two watersheds for water-quality analyses with SELDM:

1. Watersheds needed to be of sufficient size (at least around 100 $mi^2$ in drainage area) to allow for analysis of nested watersheds.

2. Watersheds needed to have substantial areas of urban, agricultural, and rural land to evaluate effects of land-use change and evaluate the importance of road crossings for different land uses.

3. Watersheds needed to be of moderate slope and elevation. High-elevation watersheds are not indicative of typical population centers where a majority of road crossings occur, especially in western Oregon.

4. Watersheds with hydrologic data (streamflow and water-quality time-series and samples) were favored over watersheds with little or no hydrologic data.

5. Watersheds with known water-quality concerns were favored.

**Table 2.** Basin characteristic statistics for select drainage areas in Oregon.

[The values for different variables shown in the rows of the table are not necessarily from the same basin; for example it is unlikely that the basin with the maximum forest area also is the basin with the maximum percentage of impervious area. **Mean basin elevation:** ft, feet; data from 30-m DEM, NHDPlus elev_cm grid, http://www.horizon-systems.com/NHDPlus/. ft, foot. **Forest area:** Estimated using ArcInfo Grid with 30-m resolution data layers from the USGS National Land Cover Dataset (1992); forest categories included: deciduous, evergreen, and mixed. Source: http://landcover.usgs.gov/natllandcover.php, accessed June 25, 2008. **Mean annual precip:** Road length in miles (mi). precip, precipitation; in/yr, inch per year. Data from 800-m resolution PRISM 1971-2000 data, http://www.prism.oregonstate.edu/products/. **Major, Minor, and State roads:** mi, miles; data from Oregon Department of Transportation. **Forest and shrub:** Percentage of forests and shrub lands from 30-m resolution USGS National Land Cover Dataset (2011; http://www.mrlc.gov/nlcd11_data.php; variable name LC11FORSHB, classes 41 to 52). **TIA:** Total impervious area as a percentage as determined from 30M resolution USGS National Land Cover Dataset (2011; http://www.mrlc.gov/nlcd11_data.php; 30M resolution USGS National Land Cover Dataset, 2011 data, http://www.mrlc.gov/nlcd11_data.php). **Number of minor, major, and State road crossings:** Estimated using NHDplus version 1 and Oregon Department of Transportation GIS layers. **Abbreviations:** mi, mile; $mi^2$, square mile; %, percent]

| Basin characteristic | Mean basin elevation (ft) | Forest area (%) | Mean annual precip (in/yr) | Major roads (mi) | Minor roads (mi) | State roads (mi) | Forest and shrub (%) | TIA (%) | Number of minor road crossings | Number of major road crossings | Number of State road crossings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **5 $mi^2$ watersheds** | | | | | | | | | | | |
| Minimum | 139 | 0.00 | 8.15 | 0.00 | 0.0 | 0.0 | 1.00 | 0.00 | 0 | 0 | 0 |
| 25th percentile | 2,220 | 0.01 | 13.1 | 0.00 | 3.8 | 0.0 | 71.5 | 0.03 | 1 | 0 | 0 |
| Median | 4,029 | 8.9 | 20.7 | 0.00 | 6.0 | 0.0 | 95.0 | 0.09 | 3 | 0 | 0 |
| 75th percentile | 4,999 | 83.7 | 53.6 | 0.1 | 10.6 | 0.0 | 99.0 | 0.30 | 5 | 0 | 0 |
| Maximum | 6,844 | 99.5 | 124 | 11.8 | 79 | 5.7 | 100 | 29.5 | 23 | 8 | 7 |
| **10 $mi^2$ watersheds** | | | | | | | | | | | |
| Minimum | 105 | 0.00 | 8.50 | 0.00 | 0.0 | 0.0 | 1.00 | 0.00 | 0 | 0 | 0 |
| 25th percentile | 2,537 | 0.04 | 12.7 | 0.00 | 7.6 | 0.0 | 72.5 | 0.05 | 1 | 0 | 0 |
| Median | 4,277 | 16.7 | 18.8 | 0.00 | 12.8 | 0.0 | 94.0 | 0.15 | 4 | 0 | 0 |
| 75th percentile | 4,948 | 78.7 | 45.5 | 2.2 | 20.1 | 0.0 | 99.0 | 0.34 | 8 | 1 | 0 |
| Maximum | 6,719 | 99.4 | 149 | 29.7 | 60 | 14.7 | 100 | 18.4 | 18 | 12 | 16 |
| **25 $mi^2$ watersheds** | | | | | | | | | | | |
| Minimum | 284 | 0.00 | 9.20 | 0.00 | 7.6 | 0.0 | 0.00 | 0.01 | 0 | 0 | 0 |
| 25th percentile | 2,598 | 0.21 | 12.5 | 0.00 | 21.8 | 0.0 | 76.0 | 0.08 | 7 | 0 | 0 |
| Median | 4,038 | 29.3 | 18.2 | 2.01 | 35.6 | 0.0 | 93.0 | 0.18 | 12 | 1 | 0 |
| 75th percentile | 4,945 | 75.2 | 49.8 | 7.3 | 53.4 | 2.0 | 98.0 | 0.39 | 20 | 3 | 0 |
| Maximum | 6,364 | 99.4 | 109 | 36.3 | 145 | 15.1 | 100 | 12.8 | 38 | 24 | 11 |
| **50 $mi^2$ watersheds** | | | | | | | | | | | |
| Minimum | 558 | 0.00 | 8.78 | 0.00 | 10.5 | 0.0 | 7.00 | 0.00 | 2 | 0 | 0 |
| 25th percentile | 2,693 | 2.04 | 13.1 | 0.00 | 47.3 | 0.0 | 85.0 | 0.07 | 17 | 0 | 0 |
| Median | 4,233 | 52.4 | 19.5 | 5.44 | 64.6 | 0.0 | 94.0 | 0.14 | 26 | 2 | 0 |
| 75th percentile | 4,955 | 87.6 | 50.4 | 11.2 | 99.0 | 2.9 | 98.0 | 0.26 | 41 | 6 | 1 |
| Maximum | 6,595 | 97.9 | 123 | 73.5 | 273 | 17.8 | 100 | 9.25 | 94 | 36 | 18 |
| **80–120 $mi^2$ watersheds** | | | | | | | | | | | |
| Minimum | 300 | 13.0 | 47.6 | 1.5 | 99.3 | 0.0 | 0.0 | 0.0 | 27 | 1 | 1 |
| 25th percentile | 989 | 78.0 | 61.4 | 11.9 | 169 | 0.2 | 72.8 | 0.1 | 59 | 6 | 5 |
| Median | 1,154 | 84.4 | 73.8 | 16.0 | 201 | 8.5 | 80.0 | 0.3 | 74 | 15 | 6 |
| 75th percentile | 2,004 | 88.6 | 81.2 | 35.8 | 254 | 18 | 89.0 | 0.8 | 99 | 22 | 12 |
| Maximum | 4,781 | 96.4 | 95.5 | 132 | 403 | 43 | 98.0 | 25.3 | 179 | 89 | 27 |
| **200 $mi^2$ watersheds** | | | | | | | | | | | |
| Minimum | 973 | 0.01 | 14.8 | 0.00 | 71.9 | 0.0 | 7.00 | 0.01 | 14 | 0 | 0 |
| 25th percentile | 3,305 | 4.0 | 18.6 | 12.0 | 174 | 0.0 | 86.0 | 0.09 | 65 | 5 | 0 |
| Median | 4,539 | 35.0 | 20.3 | 25.8 | 233 | 11.0 | 92.0 | 0.16 | 99 | 14 | 3 |
| 75th percentile | 5,108 | 77.4 | 23.5 | 37.0 | 343 | 20.0 | 96.8 | 0.27 | 142 | 24 | 12 |
| Maximum | 6,230 | 94.9 | 31.7 | 93.0 | 610 | 36.2 | 99.0 | 1.32 | 299 | 90 | 31 |

Mill Creek and Bear Creek watersheds were selected for further analysis (fig. 1, table 3). Bear Creek meets all of the selected criteria. Bear Creek has a drainage area is 362 $mi^2$ and drains agricultural and rural/forested lands (15 and 61percent, respectively) before flowing through the Medford urban area. The mean basin elevation is about 3,000 ft, which is close to the median value for watersheds of about 200 $mi^2$ in drainage area. Bear Creek is also considered an impaired waterbody and has been evaluated for concerns regarding copper, phosphorus, sedimentation, and other water-quality constituents (Oregon Department of Environmental Quality, 2018a).

Mill Creek also meets all five of the selected criteria. The total drainage area of the watershed is 114 $mi^2$. The mouth of Mill Creek is in the Salem metropolitan area, but much of the creek flows through agricultural lands (more than 60 percent) and much of the headwaters are in forested, rural areas (12–13 percent). The mean basin elevation is 526 ft. Streamflow data are available from the City of Salem, which monitors several locations along the creek and its tributaries. In addition, Mill Creek is considered an impaired waterbody and has been evaluated for concerns regarding sedimentation and many other water-quality constituents (Oregon Department of Environmental Quality, 2018b).

# Selection Of Nested Watersheds For Stormwater Analyses

Nested watersheds were selected to facilitate a wide variety of conditions in which SELDM may be applied. Road crossings were selected to obtain relatively consistent spacing between road crossings and thus present a wide variety of model scenarios.

Seven road crossings were selected for Bear Creek (fig 1*A*, table 4). Four of the road crossings were on Bear Creek, two on the large tributary, Emigrant Creek, and one on the smaller Hamilton Creek. Drainage areas of the nested watersheds ranged from 0.73 to 362 $mi^2$. It should be noted that the road crossing for Emigrant Creek at Highway 66 is upstream from Emigrant Lake, which is the only substantial lake or reservoir within either study area, but still accounts for less than 1 percent of the total drainage area.

Seven road crossings were also selected for Mill Creek (fig 1*B*, table 5), all of which were along Mill Creek. Drainage areas ranged from 9.56 to 114 $mi^2$. When possible, road crossings were also selected close to the City of Salem streamgages along Mill Creek.

# Simulated Hydrology

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, 2013). Precipitation, upstream prestorm flows, storm event runoff from the highway and the upstream basin, and flow modifications by a generic median-performance BMP were simulated using methods described by Granato (2010, 2013, 2014) and indicated in Stonewall (2019).

## Precipitation

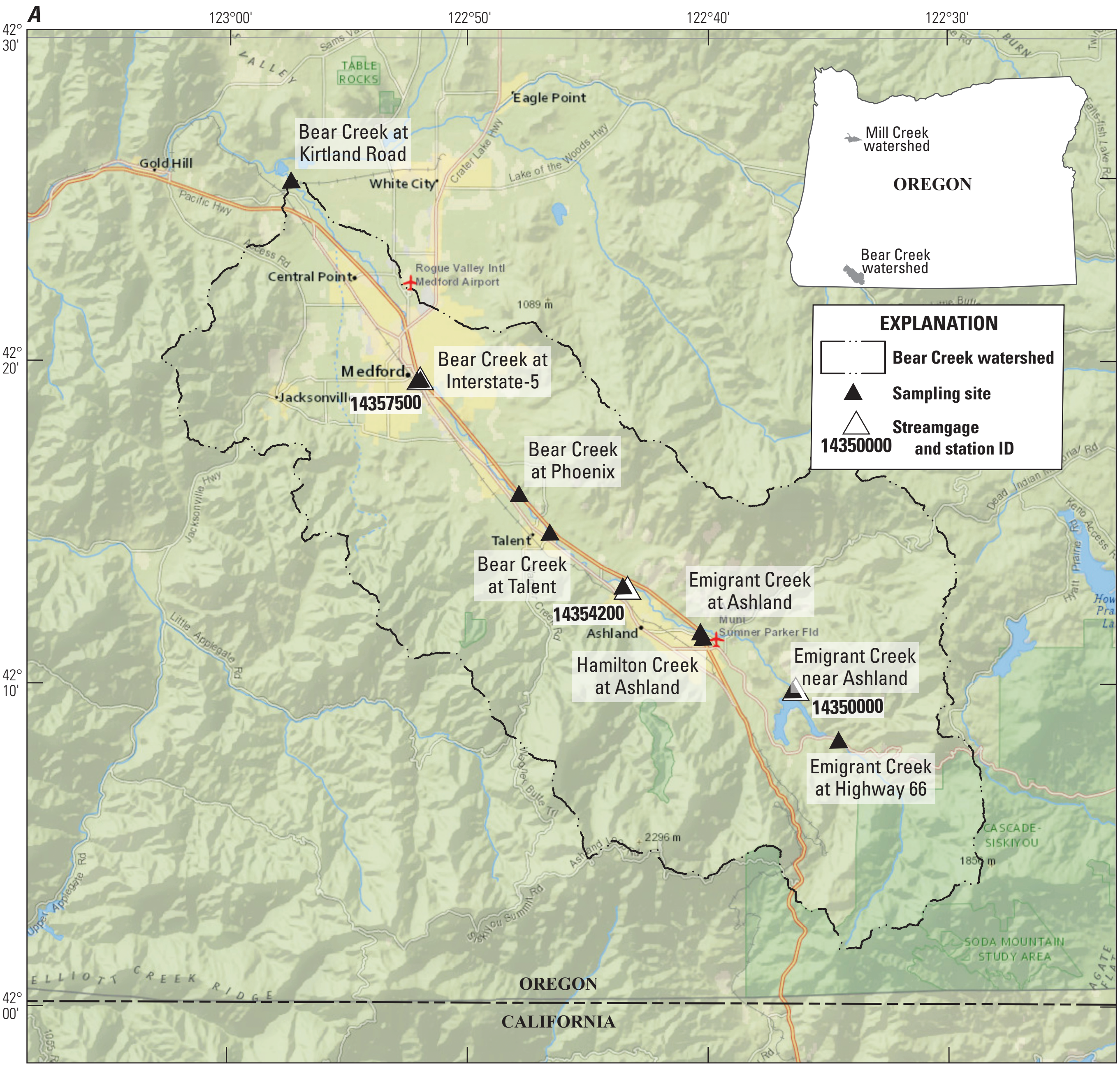
Statewide precipitation statistics for storm event volume, storm event duration, time between storm events, and number of storm events per year were derived from geographic information system (GIS) data layers developed by Risley and Granato (2014). Precipitation site characteristics and other precipitation statistics of interest were then used to investigate potential improvements to these coverages. Results were quantified by comparing the resultant statewide precipitation statistics from the Risley and Granato (2014) data layers to the network of 109 precipitation gages (not shown) used for kriging[1] methods as outlined by Risley and Granato (2014).

This analysis revealed that deriving the three precipitation statistics from the Risley and Granato 2014 GIS coverages could be improved using a regression relation with mean annual precipitation as the independent variable (table 6). The precipitation statistics for each Mill Creek and Bear Creek site were modified using this improved regression relation (table 7).

## Prestorm Streamflow

SELDM requires the estimation of several streamflow statistics at the road crossing sites to stochastically generate prestorm streamflows. These statistics include the proportion of daily streamflows that were zero and the average, standard deviation, and skew of the logarithmic daily streamflow values. All statistics are in the units of cubic feet per second per square mile [$(ft^3/s)/mi^2$] of drainage area before logarithmic transformation, except skewness, which has no units. For the purposes of this study, anthropogenic perturbations to streamflow, such as irrigation returns or diversions, were not considered. A more thorough accounting of such perturbations would be needed to derive as accurate a streamflow budget as possible for modeling purposes. However, the added complexity and uncertainty was deemed unnecessary for the demonstrative purposes of this report. The

[1] Kriging is a method of interpolation.



Base map modified from Esri, copyright 2018. Coordinate system: NAD 1983 HARN Oregon Statewide Lambert Feet Intl. Horizontal datum is North American Datum of 1983.

**Figure 1.** Locations of simulated watersheds, Bear Creek (A) and Mill Creek (*B*) watersheds, Oregon.

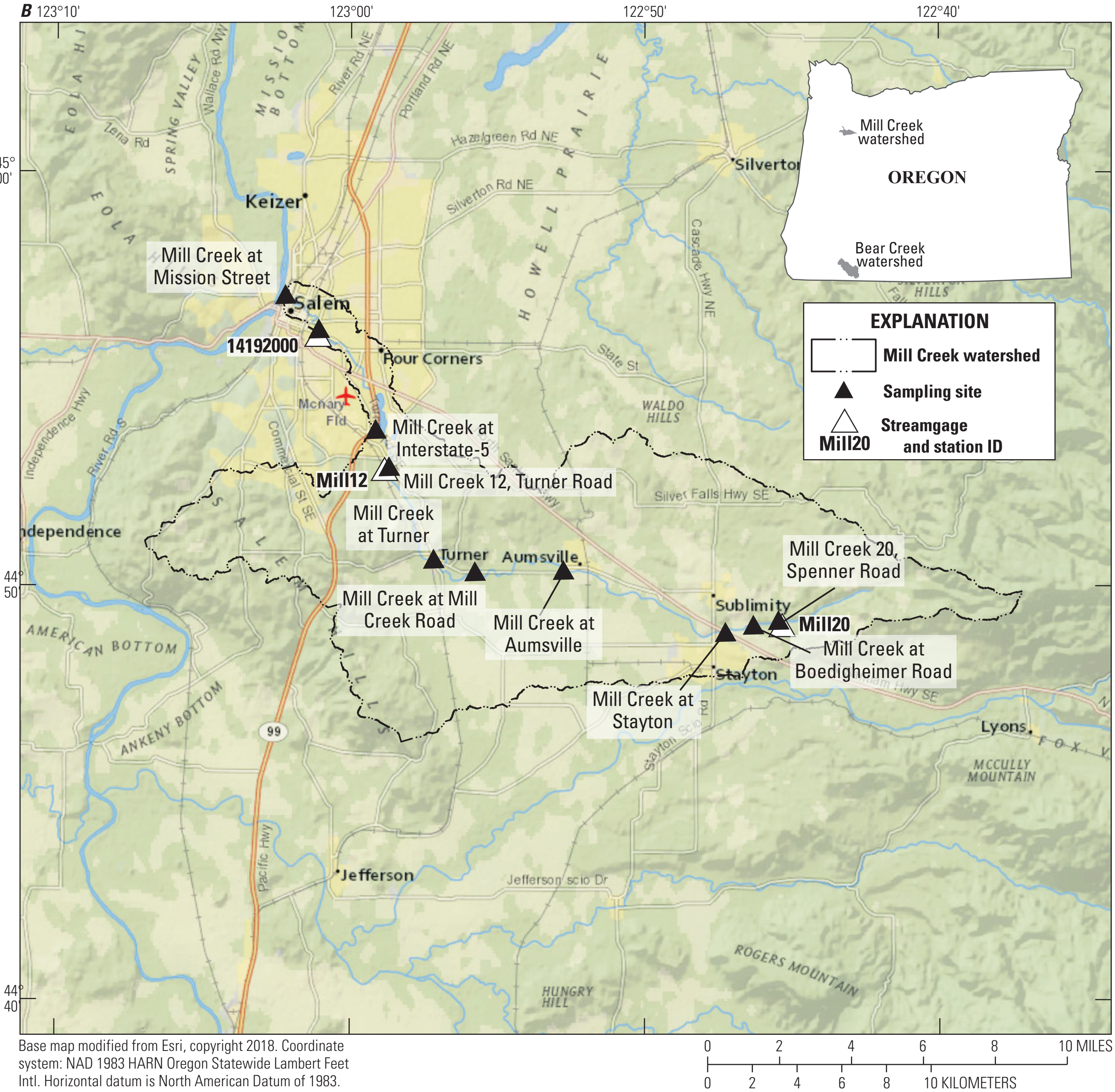



**Figure 1.—Continued**

**Table 3.** Basin characteristics of Mill Creek and Bear Creek, Oregon.

[**Description:** NLCD 2011, National Land Coverage Dataset (2011)]

| Basin characteristic | Units | Description | Bear Creek | Mill Creek |
|---|---|---|---|---|
| Latitude | decimal degrees | As entered into Oregon StreamStats application | 42.428 | 44.951 |
| Longitude | decimal degrees | As entered into Oregon StreamStats application | -122.9576 | -123.0375 |
| DRNAREA | square miles | Area that drains to a point on a stream | 362 | 114 |
| DRNDENSITY | miles per square mile | Basin drainage density defined as total stream length divided by drainage area. | 0.55 | 0.81 |
| ELEV | feet | Mean Basin Elevation | 2980 | 526 |
| ELEVMAX | feet | Maximum basin elevation | 7480 | 2170 |
| MINBELEV | feet | Minimum basin elevation | 1160 | 123 |
| RELIEF | feet | Maximum - minimum elevation | 6320 | 2050 |
| STRMTOT | miles | Total length of mapped streams in basin | 321 | 150 |
| STATE_HWY | miles | Length of state highways in basin | 128 | 43.3 |
| MAJ_ROADS | miles | Length of non-state major roads in basin | 238 | 132 |
| MIN_ROADS | miles | Length of non-state minor roads in basin | 968 | 403 |
| PRECIP | inches | Mean Annual Precipitation | 26.5 | 51 |
| LC11WATER | percent | Percent of open water, class 11, from NLCD 2011 | 0 | 1 |
| LC11BARE | percent | Percentage of barren from NLCD 2011 class 31 | 0 | 0 |
| LC11FORSHB | percent | Percentage of forests and shrub lands, classes 41 to 52, from NLCD 2011 | 61 | 12 |
| LC11HERB | percent | Percentage of herbaceous from NLCD 2011 classes 71-74 | 9 | 3 |
| LC11CRPHAY | percent | Percentage of cultivated crops and hay, classes 81 and 82, from NLCD 2011 | 15 | 63 |
| LC11WETLND | percent | Percentage of wetlands, classes 90 and 95, from NLCD 2011 | 0 | 1 |
| LC11DVOPN | percent | Percentage of developed open area from NLCD 2011 class 21 | 5 | 6 |
| LC11DVLO | percent | Percentage of developed area, low intensity, from NLCD 2011 class 22 | 5 | 9 |
| LC11DVMD | percent | Percentage of area developed, medium intensity, NLCD 2011 class 23 | 3 | 5 |
| LC11DEVHI | percent | Percentage of area developed, high intensity, NLCD 2011 class 24 | 1 | 2 |
| LC11IMP | percent | Average percentage of impervious area determined from NLCD 2011 impervious dataset | 4.85 | 8.05 |
| IMPERV | percent | Percentage of impervious area | 4.72 | 6.88 |
| FOREST | percent | Percentage of area covered by forest | 54.8 | 13 |

**Table 4.** Nested watersheds modeled within Bear Creek, Oregon.

[**Drainage area:** mi², square mile. **Latitude** and **Longitude:** Decimal degrees North and West, respectively. **Main channel length:** Total length of stream in feet (ft) based on NHDPlus version 1 stream layer (http://www.horizon-systems.com/NHDPlus/NHDPlusV1_home.php). **10-85 slope:** Slope in feet per mile (ft/mi) measured between the points which are 10 and 85 percent of the total channel length. **Ratio of DA/Highway DA:** DA, drainage area. **Upstream impervious area:** area in square miles (mi²) upstream of the road crossing that is impervious determined from 2011 National Land Cover Dataset (variable name LC11IMP)]

| Name/point crossing | Drainage area (mi2) | Latitude | Longitude | Main channel length (ft) | 10-85 slope (ft/mi) | Impervious highway drainage area (acres) | Ratio of DA/ Highway DA | Upstream impervious area (mi2) | Highway impervious fraction | Upstream impervious fraction |
|---|---|---|---|---|---|---|---|---|---|---|
| Emmigrant Creek at Highway 66 | 39.3 | 42.139 | -122.576 | 49,357.3 | 244.8 | 3.328 | 7.56E+3 | 153 | 0.89 | 0.01 |
| Emigrant Creek at Ashland | 134 | 42.195 | -122.672 | 87,561.4 | 123.6 | 2.859 | 3.00E+4 | 866 | 1.00 | 0.01 |
| Hamilton Creek at Ashland | 0.73 | 42.192 | -122.670 | 42,628.0 | 276.6 | 0.443 | 1.05E+3 | 100 | 0.64 | 0.21 |
| Bear Creek at Talent | 198 | 42.246 | -122.777 | 126,856.6 | 84.6 | 1.981 | 6.40E+4 | 2306 | 1.00 | 0.02 |
| Bear Creek at Phoenix | 231 | 42.266 | -122.798 | 137,135.4 | 77.8 | 3.561 | 4.15E+4 | 3371 | 0.63 | 0.02 |
| Bear Creek at Interstate-5 | 279 | 42.325 | -122.867 | 168,899.6 | 62.1 | 0.102 | 1.74E+6 | 5196 | 0.63 | 0.03 |
| Bear Creek at Kirtland Road | 362 | 42.427 | -122.957 | 220,706.4 | 43.9 | 0.181 | 1.28E+6 | 11,236 | 1.00 | 0.05 |

**Table 5.** Nested watersheds modeled within Mill Creek, Oregon.

[**Drainage area:** mi², square mile. **Latitude** and **Longitude:** Decimal degrees North and West, respectively. **Main channel length:** Total length of stream in feet (ft) based on NHDPlus version 1 stream layer (http://www.horizon-systems.com/NHDPlus/NHDPlusV1_home.php). **10-85 slope:** Slope in feet per mile (ft/mi) measured between the points that are 10 and 85 percent of the total channel length. **Ratio of DA/Highway DA:** DA, drainage area. **Upstream impervious area:** area in square miles (mi²) upstream rom the road crossing that is impervious determined from 2011 National Land Cover Dataset (variable name LC11IMP), http://www.mrlc.gov/nlcd11_data.php]

| Name/road crossing | Drainage area (mi2) | Latitude | Longitude | Main channel length (ft) | 10-85 slope (ft/mi) | Impervious highway drainage area (acres) | Ratio of DA / Highway DA | Upstream impervious area (mi2) | Highway impervious fraction | Upstream impervious fraction |
|---|---|---|---|---|---|---|---|---|---|---|
| Mill Creek at Boedigheimer Road | 9.56 | 44.818 | -122.772 | 41,667.2 | 141.5 | 2.261 | 2.71E+3 | 12 | 0.89 | 0.00 |
| Mill Creek at Stayton | 11.5 | 44.815 | -122.788 | 46,254.7 | 136.4 | 4.792 | 1.54E+3 | 32 | 1.00 | 0.00 |
| Mill Creek at Aumsville | 19.1 | 44.840 | -122.879 | 74,871.0 | 78.6 | 0.552 | 2.21E+4 | 1,033 | 1.00 | 0.08 |
| Mill Creek at Mill Creek Road | 55.9 | 44.839 | -122.929 | 92,799.5 | 63.7 | 0.658 | 5.44E+4 | 1,950 | 0.83 | 0.05 |
| Mill Creek at Turner | 64 | 44.844 | -122.953 | 103,088.0 | 56.8 | 0.906 | 4.52E+4 | 2,118 | 1.00 | 0.05 |
| Mill Creek at Interstate-5 | 107 | 44.897 | -122.986 | 127,896.0 | 39.4 | 6.932 | 9.88E+3 | 4,170 | 1.00 | 0.06 |
| Mill Creek at Mission Street | 114 | 44.951 | -123.037 | 135,834.0 | 27.3 | 0.181 | 4.03E+5 | 5,866 | 1.00 | 0.08 |

**Table 6.** Goodness-of-fit metrics for precipitation statistics for Oregon.

[**Abbreviations:** RMSE, root-mean-square error; MdR, median residual; MnR, mean residual]

| Coverage | RMSE | MdR | MnR |
|---|---|---|---|
| **Storm duration (hours)** | | | |
| Original Risley and Granato (2014) | 2.13 | 0.36 | -0.05 |
| Modified | 2.02 | 0.49 | -0.00 |
| **Storm volume (inches)** | | | |
| Original Risley and Granato (2014) | 0.11 | 0.04 | 0.01 |
| Modified | 0.09 | 0.01 | 0.01 |
| **Time between storm events (hours)** | | | |
| Original Risley and Granato (2014) | 36.74 | 1.82 | -0.47 |
| Modified | 35.27 | -0.21 | -0.00 |

**Table 7.** Precipitation statistics used in SELDM models for sites at Bear and Mill Creeks, Oregon.

[**Mean storm delta:** time between storms. **Abbreviations:** in., inches; precip, precipitation; no. number of; cov, covariance]

| Site | Mean annual precip (in.) | Mean no. storms | Mean storm delta (hours) | Mean storm duration (hours) | Mean storm volume (in.) | Cov annual precip (in.) | Cov no. storms | Cov storm delta (hours) | Cov storm duration (hours) | Cov storm volume (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Bear Creek** | | | | | | | | | | |
| Emmigrant at Hwy 66 | 22.2 | 36.1 | 258 | 10.3 | 0.543 | 0.355 | 0.279 | 1.72 | 0.913 | 1.08 |
| Emmigrant Ashland | 23.0 | 38.3 | 248 | 10.0 | 0.526 | 0.344 | 0.279 | 1.72 | 0.907 | 1.07 |
| Hamilton | 21.5 | 37.6 | 249 | 9.7 | 0.507 | 0.340 | 0.279 | 1.72 | 0.903 | 1.06 |
| Talent | 22.4 | 38.3 | 246 | 9.9 | 0.514 | 0.342 | 0.279 | 1.72 | 0.902 | 1.06 |
| Phoenix | 22.2 | 38.3 | 245 | 9.9 | 0.510 | 0.342 | 0.278 | 1.72 | 0.900 | 1.07 |
| Bear at I-5 | 22.0 | 37.8 | 247 | 10.0 | 0.514 | 0.344 | 0.277 | 1.72 | 0.901 | 1.07 |
| Kirtland | 22.7 | 38.9 | 239 | 10.2 | 0.519 | 0.340 | 0.274 | 1.74 | 0.899 | 1.08 |
| **Mill Creek** | | | | | | | | | | |
| Boedigheimer Rd | 44.9 | 69.6 | 120 | 13.5 | 0.676 | 0.246 | 0.196 | 1.76 | 0.944 | 1.07 |
| Stayton | 44.5 | 70.3 | 119 | 13.3 | 0.663 | 0.246 | 0.196 | 1.76 | 0.945 | 1.07 |
| Aumsville | 44.5 | 69.1 | 121 | 13.5 | 0.673 | 0.247 | 0.196 | 1.76 | 0.944 | 1.07 |
| Mill Cr Rd | 44.4 | 69.3 | 121 | 13.4 | 0.670 | 0.247 | 0.196 | 1.76 | 0.944 | 1.07 |
| Turner | 44.6 | 69.8 | 120 | 13.4 | 0.668 | 0.246 | 0.196 | 1.76 | 0.944 | 1.07 |
| Mill at I-5 | 44.3 | 68.5 | 122 | 13.4 | 0.671 | 0.247 | 0.194 | 1.76 | 0.937 | 1.08 |
| Mill at Mission | 44.2 | 68.6 | 122 | 13.3 | 0.669 | 0.247 | 0.194 | 1.76 | 0.937 | 1.07 |

following steps were used to estimate the streamflow statistics for both watersheds:

1. Determine an "index" streamgage (station) that is meant to represent the general productivity in cubic feet per second per square mile for each site within the watershed.
2. Choose several nearby streamgages of various drainage areas that encompass the drainage areas for all the streamgages in the watershed of interest (Mill or Bear Creek). Ideally the nearby streamgages will also have other similar basin characteristics such as elevation and slope.
3. Develop a relation between the drainage area and the statistic of interest needed for the SELDM.
4. Using the derived relations from step 3, calculate the new streamflow statistic for each streamgage in the watershed of interest.
5. Adjust the statistics computed from step 4 based on the residual between the index streamgage and other stations used for step 3.
6. Divide by the drainage area of the site to get the final statistics used for the SELDM model.

Calculations for prestorm flows for both watersheds are in tables 8 and 9. For illustrative purposes, these six steps are shown for the geometric mean daily streamflow of the Mill Creek at Mission Street site in the following example:

1. Three streamflow time series were considered for an index station to estimate prestorm streamflow in Mill Creek (table 10). Originally, USGS streamgage 14192000 was selected because it had the longest period of record of any station within the watershed. However, subsequent analysis indicated an especially low amount of streamflow productivity compared to other streamgages in the area [median daily streamflow of 0.84 ($ft^3$/s)/$mi^2$, table 11]. By comparison, the Mill Creek 12 streamgage indicates that streamflow is about twice as productive [1.69 ($ft^3$/s)/$mi^2$], even though it has almost the same drainage area.

It is unknown at this time, and beyond the scope of this study to determine the cause of this discrepancy. It is possible that there was more consumptive use in the Mill Creek watershed during the period of record for streamgage 14192000 when compared to current rates of consumptive use. Subsequently, the Mill Creek 12 streamgage was selected for use as the index station. It has the second longest period of record, and its streamflow productivity is within the lower bounds of the other regional streamgages.

2. The other regional streamgages selected for analysis had drainage areas ranging from 22.7 to 528 $mi^2$ (table 9). These streamgages were selected based on location, lack of streamflow regulation (anthropogenic manipulation of streamflow), and general land-use patterns. The regional streamgages tend to have higher streamflow productivity than Mill Creek 12 (table 9, column X).
3. A linear relation was found between the drainage area and the mean streamflow (fig. 2). The relation appears relatively strong, with a coefficient of determination ($R^2$) value of 0.914. However, station 14194150 appears to have relatively high leverage with a mean streamflow of more than 1,700 cubic feet per second ($ft^3$/s; table 9), which has likely inflated the $R^2$ value slightly.
4. Using the equation based on the linear relation from step 3:

$$Q_{mean} = 2.952\left(DA\right) + 114.6 \qquad (1)$$

where

$Q_{mean}$ is the mean of the daily mean values of streamflow in cubic feet per second; and

$DA$ is the drainage area of the watershed upstream from the site in square miles.

The resultant $Q_{mean}$ for the Mill Creek at Mission Street site using a drainage area of 114 $mi^2$ (table 9) is 451 $ft^3$/s.

5.For the Mill Creek 12 streamgage, the expectant $Q_{mean}$ value using equation 1 with drainage area of 105 $mi^2$ (table 11) is 425 $ft^3$/s, whereas the true value was 313 $ft^3$/s (table 9). To account for this bias, the $Q_{mean}$ from step 4 was adjusted using the equation

$$Q_{adj} = \frac{Q_{mean}}{1 + \dfrac{Q_{12_{mean}} - Q_{12}}{Q_{12}}} \qquad (2)$$

where

$Q_{adj}$ is mean of the daily mean streamflow in cubic feet per second, adjusted for the residual between Mill Creek 12 station and the regional regression;

$Q_{mean}$ is the mean of daily mean values of streamflow of the site of interest in cubic feet per second from equation 1;

$Q_{12mean}$ is the mean of daily mean values of streamflow at the Mill Creek 12 station calculated from the regional regression equation (equation 1) in cubic feet per second; and

$Q_{12}$ is the mean of daily mean values of

**Table 8.** Calculations of prestorm flows at road crossings in the Bear Creek watershed, Oregon.

[Table 8 is an Excel® file available for download at https://doi.org/10.3133/sir20195053]

**Table 9.** Calculations of prestorm flows at road crossings in the Mill Creek watershed, Oregon.

[Table 9 is an Excel® file available for download at https://doi.org/10.3133/sir20195053]

**Table 10.** Considered for determining prestorm streamflow in Mill and Bear Creeks, Oregon.

[Abbreviation: $mi^2$, square mile; USGS, U.S. Geological Survey]

| Station ID | Name | Agency | Period of record | Drainage area (mi2) |
|---|---|---|---|---|
| | | Mill Creek | | |
| 14192000 | Mill Creek at Salem, OR | USGS | 1940–78 | 110 |
| Mill Creek 12 | Mill Creek at Turner Rd[1] | City of Salem | 2006–current | 105 |
| Mill Creek 20 | Mill Creek at Spenner Rd | City of Salem | 2014–current | 8.31 |
| | | Bear Creek | | |
| 14350000 | Emigrant Creek near Ashland, OR | USGS | 1920–86 | 64.3 |
| 14354200 | Bear Creek below Ashland Creek at Ashland, OR | USGS | 1990–current | 168 |
| 14357500 | Bear Creek at Medford, OR | USGS | 1915–current | 289 |

[1] Note that this station is distinct from the Mill Creek at Turner site used for SELDM modeling. The City of Salem, Oregon streamgage is on Turner Road, but not in the town of Turner, and has a substantially larger drainage area than Mill Creek at Turner.

**Table 11.** Streamflow productivity for regional streamgage stations in or near the Bear and Mill Creek watersheds, Oregon

[Abbreviations: ID, identification; DA, drainage area; $(ft^3/s)/mi^2$ cubic feet per second per square mile]

| Station ID | Station name | DA | Median daily (ft3/s)/mi2 |
|---|---|---|---|
| | Near Mill Creek | | |
| 14185000 | South Santiam River Below Cascadia, OR | 174 | 2.89 |
| 14185800 | Middle Santiam R Near Cascadia, OR | 104 | 3.85 |
| 14200400 | Little Abiqua Creek Near Scotts Mills, OR | 9.81 | 1.94 |
| 14203750 | Gales Creek Near Glenwood, OR | 7.3 | 1.64 |
| 14205400 | East Fork Dairy Creek Near Meacham Corner, OR | 33.8 | 1.21 |
| 14211000 | Clackamas River Near Clackamas, OR | 933 | 2.83 |
| 14306500 | Alsea River Near Tidewater, OR | 334 | 1.92 |
| | Mill Creek | | |
| 14192000 | Mill Creek at Salem, OR | 110 | 0.84 |
| Mill Creek 12 | Mill Creek at Turner Rd[1] | 105 | 1.69 |
| | Near Bear Creek | | |
| 14198400 | Bull Creek Near Wilhoit, OR | 0.78 | 0.83 |
| 14308000 | South Umpqua River at Tiller, OR | 449 | 1.12 |
| 14308990 | Cow Creek Abv Galesville Res, Nr Azalea, OR. | 64.7 | 0.47 |
| 14309000 | Cow Creek near Azalea, OR | 78 | 0.68 |
| 14309500 | West Fork Cow Creek near Glendale, OR | 86.9 | 0.74 |
| 14310000 | Cow Creek near Riddle, OR | 456 | 0.50 |
| 14315500 | North Umpqua River at Toketee Falls, OR | 334.8 | 1.91 |
| 14315700 | N.umpqua R Blw Slide Ck Dam Nr Toketee Falls, OR | 336.77 | 0.35 |
| 14315950 | Fish Creek Abv Slipper Creek Nr Toketee Falls, OR | 61.6 | 1.32 |
| 14316000 | Fish Ck @ Big Camas Rngr Sta Nr Toketee Falls, OR | 68.8 | 0.77 |
| 14316455 | N.umpqua R Blw Soda Spgs Resv, Nr Toketee Falls,OR | 435.1 | 0.69 |
| 14316500 | N Umpqua River Abv Copeland Ck Nr Toketee Falls,OR | 475 | 2.55 |
| 14318000 | Little River at Peel, OR | 177 | 1.18 |
| 14327500 | Rogue River Above Bybee Creek, Nr Union Cr, OR | 156 | 2.50 |
| 14328000 | Rogue River Above Prospect, OR | 312 | 2.04 |
| 14330000 | Rogue River Below Prospect, OR | 379 | 3.03 |
| 14332000 | South Fork Rogue River Near Prospect, OR | 83.8 | 0.26 |
| 14334700 | S Fk Rogue R South Of Prospect, OR | 246 | 0.93 |
| 14335500 | South Fork Big Butte Cr Nr Butte Falls,OR | 138 | 0.76 |
| 14337500 | Big Butte Creek near Mcleod, OR | 245 | 0.51 |
| 14337800 | Elk Creek Near Cascade Gorge,OR | 78.8 | 0.63 |
| 14337830 | Elk Creek Below Alco Creek, Near Trail, OR | 111 | 0.32 |
| 14338000 | Elk Creek near Trail, OR | 129 | 0.51 |
| 14341500 | South Fork Little Butte Cr Nr Lakecreek,OR | 138 | 0.32 |
| 14347000 | Little Butte Creek Ab Eagle Point OR | 269 | 0.32 |
| 14348000 | Little Butte Cr Bl Eagle Point OR | 293 | 0.35 |
| 14361700 | Carberry Creek near Copper, OR | 68.9 | 1.18 |
| 14362000 | Applegate River near Copper, OR | 225 | 1.14 |
| 14363000 | Applegate River near Ruch, OR | 302 | 0.62 |
| 14366000 | Applegate River near Applegate, OR | 483 | 0.57 |
| 14375000 | Sucker Creek Near Holland, Oreg. | 76.2 | 1.54 |
| 14375100 | Sucker Creek Blw Little Grayback Ck, Nr Holland,OR | 83.9 | 1.32 |
| 14377000 | Illinois River At Kerby, OR | 364 | 1.42 |
| 14377100 | Illinois River near Kerby, OR | 380 | 1.29 |
| | Bear Creek | | |
| 14350000 | Emigrant Cr Nr Ashland,OR | 64.3 | 0.14 |
| 14354200 | Bear Creek Blw Ashland Creek At Ashland, OR | 168 | 0.26 |
| 14357500 | Bear Creek At Medford, OR | 289 | 0.18 |

[1] Note that this station is distinct from the Mill Creek at Turner site used for SELDM modeling. The City of Salem gage is on Turner Road, but not in the town of Turner, and has a substantially larger drainage area than Mill Creek at Turner.

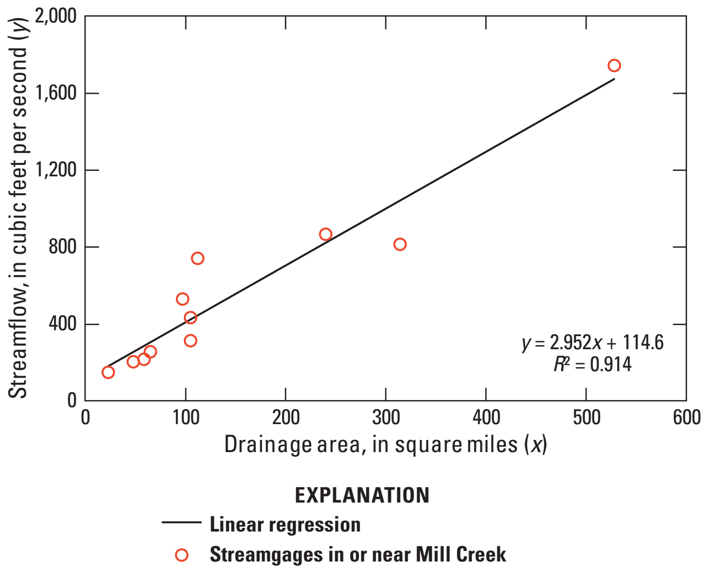



**Figure 2.** Relation between drainage area and mean streamflow for streamgages in and near the Mill Creek watershed, Oregon.

streamflow Mill Creek 12 station in cubic feet per second.

The resulting value for Mill Creek at Mission Street was 332 $ft^3/s$. For comparison, $Q_{12mean}$ was 313 $ft^3/s$. The site at Mill Creek at Mission Street has a slightly larger drainage area (114 $mi^2$ compared to 105 $mi^2$ for Mill Creek 12 station). The resulting $Q_{adj}$ value is more indicative of the measured amount of streamflow in Mill Creek, while still allowing for scaling based on drainage area using the relation between streamflow and drainage area in the region.

Dividing $Q_{adj}$ by the drainage area yields a final value of 2.91 $(ft^3/s)/mi^2$ for Mill Creek at Mission Street (table 9).

A similar procedure was used for the Bear Creek sites with the following differences: (1) rather than using an index station in step 1, all three USGS streamgages in the Bear Creek watershed (table 8) were evaluated, and the basin with the median value was used as the index station for each statistic; and (2) all analyses were performed in log space, which prevents negative values for the resulting streamflow statistics of the smallest watershed (Hamilton Creek). All streamflow statistics for Bear and Mill Creek watersheds used to simulate prestorm streamflows are listed in table 12.

## Runoff Coefficients

SELDM simulates runoff from precipitation by using stochastic runoff coefficients simulated with the Pearson type III distribution (Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988). The stochastic-runoff coefficient statistics used in the analysis of highway-runoff volumes were calculated by using the standard SELDM values for the average (0.785), standard deviation (SD; 0.1917), and skew (-1.19) of runoff coefficients for sites that are fully impervious; these statistics were calculated by using rainfall-runoff data from 58 highway-runoff monitoring sites (Granato, 2013). The stochastic-runoff coefficient statistics used in the analysis of non-highway-runoff volumes were calculated by using values for the average, standard deviation, and skew of runoff coefficients for non-highway sites as a function of imperviousness; these statistics were calculated by using rainfall-runoff data from 167 non-highway-runoff monitoring sites (Granato, 2010, 2013). All highway and upstream runoff coefficient statistics are calculated by default in SELDM using the highway impervious fractions and upstream impervious fractions (see section, “Example Runoff-Quality Simulations,” for details based on individual simulations).

Highway impervious fractions ranged from 0.63 to 1 (tables 4 and 5), which resulted in average highway-runoff coefficients ranging from 0.506 to 0.785 (fully impervious). For this study, most analyses used the maximum value of 0.785 (which assumes the highway was completely impervious). Lower values were used in places such as Bear Creek at Phoenix (fig. 3), where lanes of the highway were separated by areas of pervious soil and (or) vegetation, usually in the form of a median.

Average upstream basin runoff coefficients ranged from 0.129 (presumed completely undeveloped and completely pervious) to 0.177 (Hamilton Creek, which was the most urbanized of any of the nested watersheds with a total impervious area (TIA) of 100 acres (0.156 $mi^2$) and a drainage area of 0.73 $mi^2$ for an impervious percentage of about 21 percent. Most average upstream basin runoff coefficients were closer to the minimum value, as the impervious fraction of most of the watersheds is less than 10 percent.

**Table 12.** Streamflow statistics used to simulate prestorm conditions in the Bear and Mill Creek watersheds, Oregon.

[**Abbreviations:** Q, streamflow in cubic feet per second per square mile; SD, standard deviation; Med, median]

| Site | Proportion of zero streamflows | Mean Q | SD Q | Skew Q | Med Q |
|---|---|---|---|---|---|
| Emigrant Creek at Highway 66 | 0 | 0.483 | 4.36 | 0.15 | 0.492 |
| Emigrant Creek at Ashland | 0.02 | 0.527 | 3.76 | 0.16 | 0.533 |
| Hamilton Creek at Ashland | 0.16 | 0.364 | 7.05 | 0.15 | 0.28 |
| Bear Creek at Talent | 0 | 0.541 | 3.58 | 0.16 | 0.547 |
| Bear Creek at Phoenix | 0 | 0.547 | 3.52 | 0.16 | 0.552 |
| Bear Creek at Interstate-5 | 0 | 0.555 | 3.44 | 0.16 | 0.559 |
| Bear Creek at Kirtland Road | 0 | 0.565 | 3.33 | 0.16 | 0.569 |
| Mill Creek at Boedigheimer Road | 0 | 14.661 | 1.83 | -0.57 | 9.957 |
| Mill Creek at Stayton | 0 | 12.345 | 1.83 | -0.54 | 8.423 |
| Mill Creek at Aumsville | 0 | 7.804 | 1.85 | -0.42 | 5.415 |
| Mill Creek at Mill Creek Road | 0 | 3.28 | 1.94 | 0.17 | 2.419 |
| Mill Creek at Turner | 0 | 2.982 | 1.97 | 0.3 | 2.222 |
| Mill Creek at Interstate-5 | 0 | 2.158 | 2.08 | 0.16 | 1.676 |
| Mill Creek at Mission Street | 0 | 2.083 | 2.09 | 1.09 | 1.627 |


**Figure 3.** Photograph of Interstate-5 crossing of Bear Creek, Phoenix, Oregon. (Image capture June 2017, Google Maps, Street View. ©2018 Google, used with permission)

## Storm Event Hydrographs

Three statistics related to the shape of the modeled hydrograph are needed to estimate the hydrograph recession factor (HRF) (also sometimes referred to as the "hydrograph recession ratio"), which is the ratio of the falling limb duration to the rising limb duration of a runoff hydrograph (Granato, 2013). The minimum, most probable value (MPV) (for this study, the mean value was used as MPV), and maximum HRFs were derived by evaluating the hydrograph shape of nearby gaged watersheds as well as gaged watersheds that were not within the same ecoregion but which had drainage area and other basin characteristics that were similar to the watershed of interest.

For the Bear Creek watershed, eight watersheds were evaluated, ranging in drainage areas from 0.78 to 380 $mi^2$ (table 13). For each HRF statistic, a regression was developed evaluating drainage area against the statistic of interest (example in fig. 4). Although these regression relations are relatively weak, the resulting statistics are surmised to be more accurate than taking a simple mean of all stations, because there is a statistically significant relation between the drainage areas and the HRF statistics (at a significance value of 0.05). Four of the sites used were within the Bear Creek watershed.

An identical approach was used for the Mill Creek sites. The five watersheds used for analysis had drainage areas ranging from 8.31 to 240 $mi^2$. Two of the index stations used were within the Mill Creek watershed (Mill Creek 12 and Mill Creek 20).

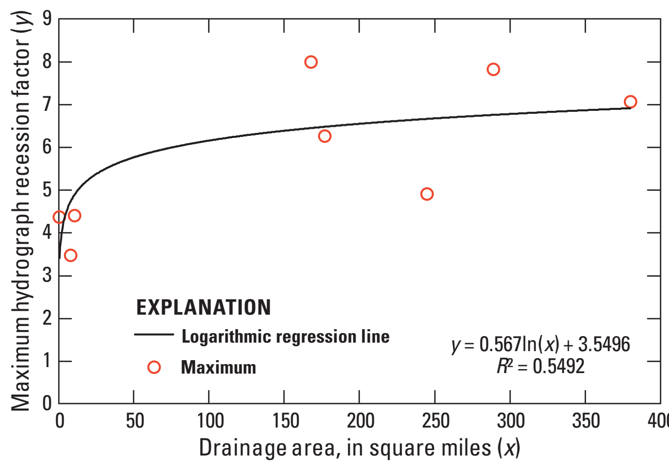



**Figure 4.** Relation between watershed drainage area and maximum hydrograph recession factor, Bear Creek, Oregon.

**Table 13.** Hydrograph recession factors from watersheds near Bear and Mill Creeks, Oregon.

[**Abbreviations:** U.S. Geologial Survery, USGS; COS, City of Salem; $mi^2$, square mile; HRF, Hydrograph Recession Factor; Min, minimum; Max, maximum; ln, natural log; DA, drainage area]

| USGS/COS station ID | Drainage area (mi2) | Min HRF | Max HRF | Mean HRF |
|---|---|---|---|---|
| Bear Creek sites | | | | |
| 14318000 | 177 | 1.21 | 6.27 | 2.05 |
| 14198400 | 0.78 | 1.03 | 4.37 | 2.22 |
| 14377100 | 380 | 1.70 | 7.06 | 3.41 |
| 14337500 | 245 | 1.57 | 4.91 | 2.80 |
| 14357500 | 289 | 1.42 | 7.83 | 3.38 |
| 14354200 | 168 | 1 | 8 | 3.5 |
| 14353500 | 8.14 | 1.05 | 3.48 | 2.42 |
| 14353000 | 10.7 | 1.13 | 4.41 | 2.14 |
| Mill Creek sites | | | | |
| 14190500 | 240 | 1.00 | 4.23 | 2.39 |
| 14201340 | 89.41 | 1.00 | 3.87 | 1.79 |
| 14201500 | 58.7 | 1.00 | 5.58 | 2.81 |
| 14191500/Mill12 | 105 | 1.00 | 3.05 | 1.90 |
| Mill 20 | 8.31 | 1.00 | 2.75 | 1.82 |
| Equations used to calculate Bear Creek HRF | | | | |
| Factor | Equation | | | |
| Min HRF | 0.0795 ln (DA) + 0.9486 | | | |
| Ave HRF | 0.1762 ln(DA) + 2.0438 | | | |
| Max HRF | 0.567 ln(DA) + 3.5496 | | | |
| Equations used to calculate Mill Creek HRF | | | | |
| Factor | Equation | | | |
| Min HRF | No equation, constant value of 1 for all DAs | | | |
| Ave HRF | 0.1075 ln (DA) + 1.6947 | | | |
| Max HRF | 0.3508 ln(DA) + 2.4357 | | | |

## Simulated Water Quality

SELDM includes three methods for simulating the quality of runoff and receiving waters upstream from the site of interest (Granato, 2013). Runoff quality from the site of interest (either the highway or the developed area simulated as a highway site) can be simulated as a random variable (the “Highway Random” module in SELDM) or as a dependent variable. Stormflow quality from the upstream basin can be simulated as a random variable, a dependent variable, or as a water-quality transport curve. In each case, available water-quality data are used to calculate statistics that represent the location and scatter of concentrations, which are used to simulate random long-term populations of concentration data. Downstream concentrations are calculated as the sum of highway runoff and upstream stormflow loads divided by the downstream stormflow (fig. 5). The populations of downstream concentrations indicate the level of risk for adverse effects of runoff on receiving water quality.

Available data for simulating runoff and receiving water quality are limited in comparison to the number of sites where estimates of water quality may be needed. For example, Granato and others (2009) identified 24,581 USGS stream water-quality monitoring stations with at least one measurement of paired concentration (of one or more constituents) and streamflow across the conterminous United States, but there are about 7.5 million miles of streams documented in the National Hydrography Dataset (Arnold, 2014). Granato and others (2009) identified 243 stream water-quality monitoring stations in Oregon and it is estimated that there are 300,878 mi of streams, including 87,551 mi of perennial streams, in Oregon (U.S. Environmental Protection Agency, 2013b). Runoff-quality monitoring data also are limited. Data representing highway-pavement runoff currently are available from seven sites in Oregon (Granato and others, 2018). In comparison, ODOT owns and maintains about 8,000 mi of roadways, local governments operate about 47,000 mi of roadways, and Federal land management agencies manage about 21,000 mi of roadways in Oregon (Oregon Department of Transportation, 2017). ODOT maintains approximately 2,736 bridges (Joseph Bond, ODOT, written commun., May 2018) and about 34,000 to 40,000 culverts (Robert Trevis, ODOT, written commun. May 2018). Selecting runoff and receiving water-quality statistics from monitored sites to represent runoff quality at an unmonitored site is not a well-defined process. Robust methods are needed to use available data from monitored sites to estimate potential effects of runoff at unmonitored sites. Because data are limited in comparison to the number of potential sites of interest and because the current study did not include a field-monitoring effort to generate site-specific data, available data are used to represent water quality at the sites of interest. State data were used when possible, but national data were used in other instances. This report evaluates the effect of mitigation measures rather than predict a series of actual EMCs that would be measured at the simulated road crossings. However, water-quality statistics were selected to simulate data populations that could be expected to occur at sites in Oregon.

In this study, three water-quality constituents were evaluated: suspended sediment concentration (USGS and USEPA parameter code p80154), total phosphorus (USGS and USEPA parameter code p00665) and total copper (USGS and USEPA parameter code p01042) (table 14). Suspended sediment concentration (SSC) was chosen as a constituent of interest, as it is one of the more commonly and easily measured constituents in Oregon stream water. In addition, SSC is often used to infer the prevalence of other water-quality constituents, such as pesticides and heavy metals (Baker, 1980; Tanner and Lee, 2004; Hladik and others, 2009; Granato and Jones, 2016). SSC was simulated to characterize sediment concentrations rather than total suspended solids (TSS; USEPA parameter code p00530) concentrations. TSS is a commonly used measure of SSC in discharges and in receiving waters because it was the first method adopted for analysis of treated wastewaters and so was adopted into the Federal Water Pollution Control Act of 1948 (commonly known as the Clean Water Act, U.S. Code Title 33, Chapter 26). However, the USGS has determined the TSS method to be “fundamentally unreliable for the analysis of natural-water samples” based on multiple studies conducted to compare the analysis results of both methods (SSC and TSS) from thousands of samples (Gray and others, 2000, Glysson and others 2000; Ward and Yorke, 2000). Subsequent receiving water studies also have indicated similar results (Galloway and others, 2005, Landers and others, 2007; Coon and others, 2009). Runoff-quality studies also indicate that TSS is an unreliable and biased measure of sediment concentrations in runoff (Bent and others, 2001; Guo, 2002, Waschbusch, 2003; Clark and Siu, 2008; Ying and Sansalone, 2008; Granato and Cazenas, 2009; Selbig and Bannerman, 2011). Furthermore, SSC values are more commonly available for documenting stream water quality than are TSS values. For example, Granato and others (2009) did data mining within the USGS National Water Information System (USGS, 2017) and found 275,950 paired values of SSC and flow from 7,477 water-quality monitoring sites nationwide and only 84,346 paired values of TSS and flow from 2,397 water-quality monitoring sites nationwide. Because SSC measurements are not as common in highway-runoff-quality datasets, and because it was surmised that the SSC-TSS relation introduces less uncertainty than other aspects of SELDM modeling, SSC was estimated from TSS measurements in runoff for the simulations done for this study (see section, “Highway-Runoff Quality”).

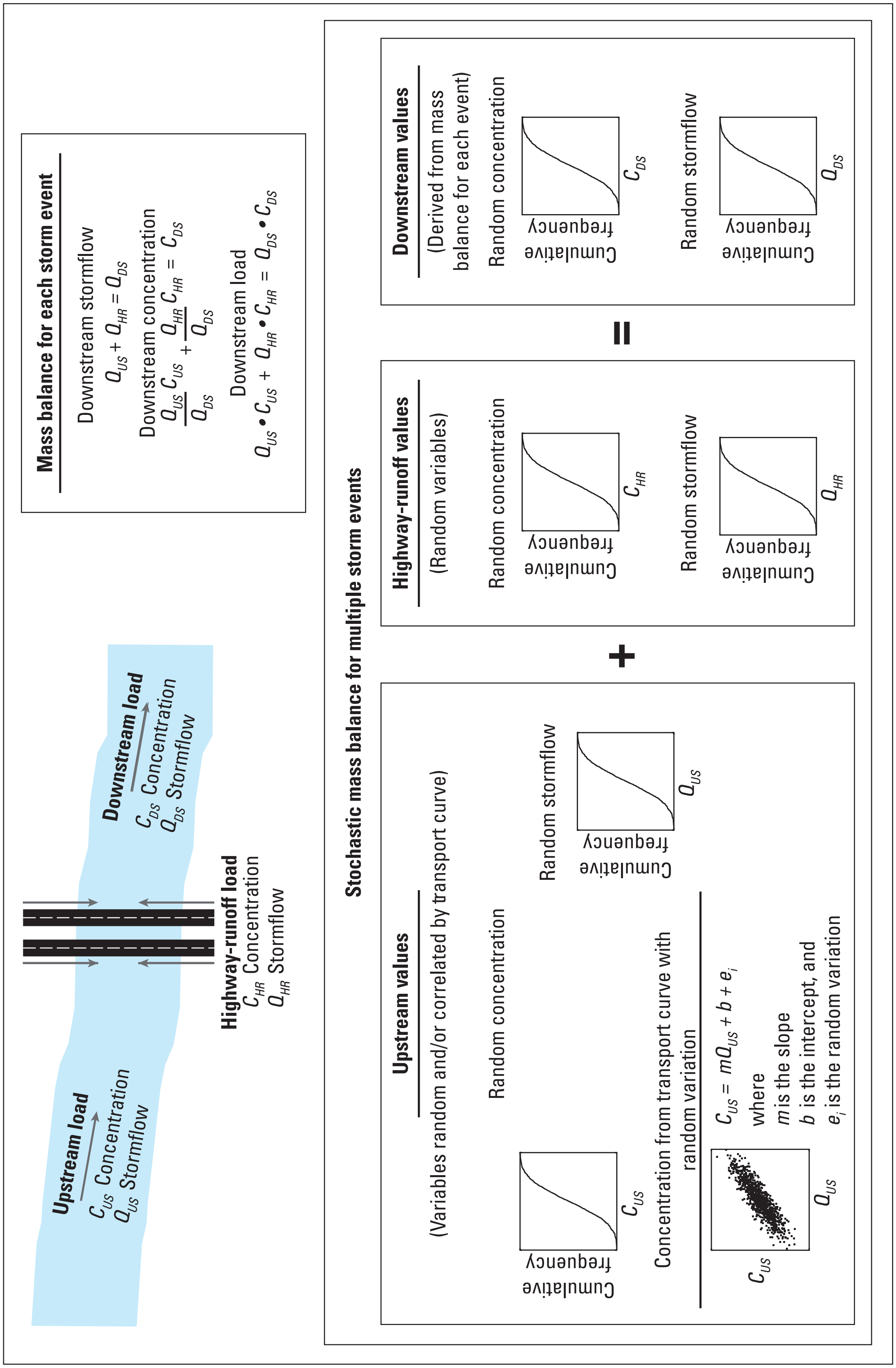



**Figure 5.** Components of the Stochastic Empirical Loading and Dilution Model.

**Table 14.** Streamflow runoff water-quality constituents of interest.

[**Oregon data in NWIS:** U.S. Geological Survey National Water Information Systems (NWIS), U.S. Geological Survey (2017). **Streamflow water quality data in SWQDM:** Surface-Water Quality Data Miner (SWQDM) from Granato and others (2009). The number of sites and samples of copper are only of those sampled after 1993, when more consistent sampling methodologies were implemented. **Pcode:** U.S. Environmental Protection Agency (EPA) parameter code. **Abbreviations:** TCu, total copper; TP, total phosphorus; SSC, suspended sediment concentration; µg/L, micrograms per liter; mg/L, milligrams per liter]

| Constituent | Pcode | Pcode definition | Oregon data in NWIS | | Oregon highway runoff data in the SWQDM | |
|---|---|---|---|---|---|---|
| | | | Sites | Samples | Sites | Samples |
| TCu | p01042 | Copper, water, unfiltered, recoverable, µg/L | 233 | 52,155 | 5 | 7 |
| TP | p00665 | Phosphorus, water, unfiltered, mg/L | 1335 | 79,671 | 113 | 1,347 |
| SSC | p80154 | Suspended sediment concentration, mg/L | 583 | 29,049 | 97 | 5,114 |

TP was selected for this study because nutrients are a common concern in Oregon and throughout the United States, and TP data are readily available for highway runoff, receiving waters, and BMP performance (Athayde and others, 1983; Granato and Cazenas, 2009; Granato and others, 2009; Leisenring and others, 2010; U.S. Environmental Protection Agency, 2013a). Phosphorus has also been identified in Oregon as a major contributor to eutrophication and harmful algal blooms (Oregon Department of Environmental Quality, 2011). The ODEQ listed 55 streams or stream segments in 10 sub-basins with phosphorus TMDLs (Oregon Department of Environmental Quality, 2012).

TCu was selected for study because of its detrimental effects to salmon and other fish important to the regional economy and local tribes (Buckley and others, 1982; McIntyre and others, 2012). In addition, copper is a common component in brake pads (Engberg, 1995; Hulskotte and others, 2007) and the abrasion of those pads disperses particulate copper to roadways, making copper a commonly occurring constituent in highway runoff. Although copper levels are not frequently monitored on Oregon roads and in Oregon watersheds, the constituent was evaluated by Risley and Granato (2014).

Anthropogenic organic compounds were not considered for selection. Data indicate that concentrations of many of these compounds are near or below detection limits in highway runoff during most storm events (Granato and Cazenas, 2009; Smith and Granato, 2010).

## Random Runoff-Quality Analysis

The quality of runoff from the highway and developed areas was simulated as random runoff-quality values by using EMC data from State datasets (see sections, “Highway-Runoff Quality” and “Developed-Area Runoff Quality”). TP, TCu, and SSC were evaluated as examples to demonstrate annual loading and receiving-water mixing analyses in basins with stormwater runoff from developed areas.

In SELDM, random runoff-quality EMCs are simulated by using the frequency-factor method (eq. 3). The frequency factor is calculated using the following equation:

$$\log_{10}(C_i) = M + \mathrm{SD} \times K_i \qquad (3)$$

where

- $i$ is the instance of simulation, which ranges from one to the number of simulated storm events;
- $C_i$ is the $i^{th}$ simulated concentration;
- $M$ is the mean of the logarithms of concentration;
- SD is the standard deviation of the logarithms of concentration; and
- $K_i$ is the Pearson Type III random variate (Granato, 2013).

The mean value ($M$) sets the magnitude of the center of the simulated sample. The magnitude of the SD controls the variation of concentrations above and below the mean; larger SD values will result in a larger range in simulated values. The Pearson Type III random variate ($K_i$), which is a function of the skew (Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988; Granato, 2013), is the value generated by SELDM. If the skew is equal to zero, then $K_i$ is a normal (Guassian) random variate. The SELDM simulations that use a modified form of the precipitation statistics from Risley and Granato (2014) result in a range of 1,341–1,410 simulated storm events for sites in the Bear Creek watershed, and 1,944–1,974 simulated storm events for sites in the Mill Creek watershed. In theory, the associated range of normal $K_i$ values would be about ±3.184 for the Bear Creek simulations and about ±3.285 for the Mill Creek simulations, given the number of simulated events. However, SELDM generates $K_i$ values randomly, and more extreme $K_i$ values may be generated in any simulation. If the skew is nonzero, then the $K_i$ values will be skewed (Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988), which increases the probability that extreme $K_i$ values may be generated

(Granato, 2013). To understand why extreme outliers may not have extreme percentiles, it is important to understand that the plotting positions written to the output files by SELDM are the sample statistics. The plotting positions are calculated from the ranks of the output values rather than the population statistics, which are the percentiles based on the random number that is generated. However, it is the magnitude of SD values that controls the effect of $K_i$ values on simulated concentrations. Therefore, statistics used for simulation data warrant careful selection.

In this study, the constituents were simulated by using the logarithms of concentrations because EMC data commonly fit a lognormal or log-Pearson Type III distribution (Di Toro, 1984; Novotny, 2004; Granato and others, 2009; Granato, 2013). If data were simulated as lognormal and the analysis done in log-space, the skew would be set equal to zero, which linearizes the distribution of generated data with respect to the logarithmic and probability axes. In comparison, dataset distributions with negative skews are concave down when plotted on a probability axis, which would result in lower values at both ends of the distribution than would be produced with a lognormal distribution. Dataset distributions with positive skews are concave up, which would result in higher values at both ends of the distribution than would be produced with a lognormal distribution. Large positive skew values, when coupled with large SD values, may produce unrealistic concentrations, flows, and loads if an extreme random number is generated (Risley and Granato, 2014; Smith and others, 2018). Because monitoring data commonly are limited, with many datasets commonly having fewer than 40 sampled storm events per site, generating a long-term record set of many events (more than 1,300 and 1,900 events in the Bear Creek and Mill Creek watersheds, respectively) required extrapolation beyond the percentiles of the original data; therefore, careful selection of representative statistics was warranted.

## Highway-Runoff Quality

The quality of runoff from the developed areas, which includes highway areas, was simulated by using EMC data from ODOT (Herrera Environmental Consultants, Inc., 2008, 2011, 2015a, 2015b, 2016; Bloomquist, 2009; Nason and others, 2011; Nason, Bloomquist, and others, 2012; Nason, Sprick, and others, 2012). ODOT did an extensive assessment of the data to verify that site characteristics, storm-event information, and concentration data were complete and correct. The USGS, in cooperation with the FHWA, entered the data into version 1.0.0b of the Highway Runoff Database (HRDB) (Granato, 2018; Granato and others, 2018). The HRDB graphical-user interface was used to calculate highway-runoff concentration statistics. The HRDB uses the robust regression on order statistics method (Granato and Cazenas, 2009) to estimate statistics for sites with one or more values below the reported detection limits (censored data).

Estimated concentrations of SSC are calculated from TSS concentrations measured at highway-runoff monitoring sites in Oregon by using a regression equation developed by Granato and Jones (2017). They applied the maintenance of variance type 1 (MOVE.1) method to 90 paired TSS and SSC measurements from multiple sites from the HRDB (Granato and Jones, 2017). The SSC concentrations for sites in Oregon were then calculated by using TSS concentrations measured at sites in Oregon by using the MOVE.1 equation:

$$\log_{10}(\text{SSC}) = -0.4889 + 1.374 \times \log_{10}(\text{TSS}) \qquad (4)$$

SELDM can be used to simulate one constituent as a dependent variable of another by using a regression equation with random variability (Granato, 2013; Granato and Jones, 2017). In this case, however, this MOVE.1 equation was used calculate the statistics in table 15 that will be used to directly simulate SSC values as a random variable. This approach, using individual TSS values to estimate the associated SSC values, was selected for the highway-runoff simulations because there are limited SSC data in the Oregon highway-runoff dataset.

There are wide ranges in the site statistics for the four runoff-quality constituents (table 15). For example, the maximum geometric mean values are 6.3, 2.3, 5.9, and 12 times the minimum geometric mean values for TSS, TP, TCu, and SSC, respectively. Information about the uncertainty in the sample statistics also is included in the table. The standard error of the estimate and the 95-percent confidence interval of the average, SD, and skew of the statistics of the logarithms of data were calculated by using methods specified by the Interagency Advisory Committee on Water Data (1982). Although the sample sizes are often adequate (ranging from 9 to 32 samples per site), the 95-percent confidence intervals for the average, standard deviation, and skew of the measured concentrations are substantial. Use of the lognormal distribution to simulate constituent concentrations is consistent with the finding of many studies on the quality of highway and urban runoff (Athayde and others, 1983; Di Toro, 1984; Driscoll and others, 1990; Van Buren and others, 1997; Novotny, 2004; National Research Council, 2009).

**Table 15.** Mean, standard deviation, and skew of the common (base 10) logarithms of event-mean concentrations in composite samples of highway and bridge-deck runoff collected from monitoring sites in Oregon, 2008–16.

[The alpha-numeric identifiers starting with "p" are the U.S. Environmental Protection Agency parameter codes. Numbers have been rounded to three significant figures. The standard error of the estimate (SEE) and 95-percent confidence interval (95% CI) were calculated by using equations in the Interagency Advisory Committee on Water Data (1982) Bulletin 17B. If the 95% CI crosses zero, the calculated statistic is not significantly different from zero. **Abbreviations:** TCu, total copper; TP, total phosphorus; SSC, suspended sediment concentration; AADT, average annual daily traffic; mg/L, milligram per liter; SEE; standard error of the estimate; µg/L, microgram per liter; --, not calculated]

| Monitoring site | Road type | Limited access | AADT | Sample count | Censored count | Geometric mean | Median |
|---|---|---|---|---|---|---|---|
| TSS: solids, suspended, water, mg/L (p00600) | | | | | | | |
| Oregon U.S. Route 20, Bend | 4-lane at grade | No | 21,400 | 9 | 1 | 112 | 2.04 |
| U.S. Route 26, Wemme | 5-lane at grade | No | 15,800 | 29 | 0 | 117 | 2.00 |
| U.S. Route 30, Portland | 4-lane cut/fill | No | 23,000 | 25 | 0 | 83.2 | 1.81 |
| Interstate I-5 Fremont Bridge, Portland | 8-lane bridge | Yes | 145,100 | 26 | 0 | 170 | 2.41 |
| St. Johns Bridge, U.S. Route 30BY, Portland | 4-lane bridge | No | 30,000 | 11 | 0 | 52.5 | 1.81 |
| Oregon U.S. Route 20, Corvallis | 3-lane at grade | No | 8,000 | 26 | 0 | 26.9 | 1.39 |
| Median of sites | -- | -- | -- | 26 | 0 | 97.6 | 1.91 |
| Lumped data | -- | -- | -- | 126 | 1 | 81.3 | 1.87 |
| TP: phosphorus, water, unfiltered, mg/L per liter (p00665) | | | | | | | |
| Oregon U.S. Route 20, Bend | 4-lane at grade | No | 21,400 | 9 | 0 | 0.377 | -0.481 |
| U.S. Route 26, Wemme | 5-lane at grade | No | 15,800 | 31 | 2 | 0.163 | -0.699 |
| U.S. Route 30, Portland | 4-lane cut/fill | No | 23,000 | 21 | 0 | 0.209 | -0.721 |
| Interstate I-5 Fremont Bridge, Portland | 8-lane bridge | Yes | 145,100 | 20 | 0 | 0.376 | -0.409 |
| Median of sites | -- | -- | -- | 21 | 0 | 0.293 | -0.590 |
| Lumped data | -- | -- | -- | 81 | 2 | 0.237 | -0.620 |
| TCu: copper, water, unfiltered, recoverable, µg/L (p01042) | | | | | | | |
| Oregon U.S. Route 20, Bend | 4-lane at grade | No | 21,400 | 9 | 2 | 24 | 1.36 |
| U.S. Route 26, Wemme | 5-lane at grade | No | 15,800 | 32 | 0 | 15.1 | 1.21 |
| U.S. Route 30, Portland | 4-lane cut/fill | No | 23,000 | 25 | 0 | 23.4 | 1.39 |
| Interstate I-5 Fremont Bridge, Portland | 8-lane bridge | Yes | 145,100 | 26 | 0 | 57.5 | 1.81 |
| St. Johns Bridge, U.S. Route 30BY, Portland | 4-lane bridge | No | 30,000 | 10 | 0 | 30.9 | 1.5 |
| Oregon U.S. Route 20, Corvallis | 3-lane at grade | No | 8,000 | 13 | 0 | 9.7 | 0.924 |
| Median of sites | -- | -- | -- | 19 | 0 | 23.7 | 1.38 |
| Lumped data | -- | -- | -- | 115 | 2 | 23.7 | 1.36 |
| SSC: suspended sediment concentration, mg/L (p80154); estimated from TSS | | | | | | | |
| Oregon U.S. Route 20, Bend | 4-lane at grade | No | 21,400 | 9 | 1 | 196 | 2.32 |
| U.S. Route 26, Wemme | 5-lane at grade | No | 15,800 | 29 | 0 | 229 | 2.27 |
| U.S. Route 30, Portland | 4-lane cut/fill | No | 23,000 | 25 | 0 | 142 | 2 |
| Interstate I-5 Fremont Bridge, Portland | 8-lane bridge | Yes | 145,100 | 26 | 0 | 375 | 2.82 |
| St. Johns Bridge, U.S. Route 30BY, Portland | 4-lane bridge | No | 30,000 | 11 | 0 | 75 | 2 |
| Oregon U.S. Route 20, Corvallis | 3-lane at grade | No | 8,000 | 26 | 0 | 30.1 | 1.43 |
| Median of sites | -- | -- | -- | 26 | 0 | 169 | 2.135 |
| Lumped data | -- | -- | -- | 126 | 1 | 136 | 2.08 |

**Table 15.** Mean, standard deviation, and skew of the common (base 10) logarithms of event-mean concentrations in composite samples of highway and bridge-deck runoff collected from monitoring sites in Oregon, 2008–16.—Continued

| Monitoring site | Common (base 10) logarithms | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | | | Standard deviation | | | Skew | | |
| | Value | SEE | 95% CI | Value | SEE | 95% CI | Value | SEE | 95% CI |
| TSS: solids, suspended, water, mg/L (p00600) | | | | | | | | | |
| Oregon U.S. Route 20, Bend | 2.05 | 0.156 | 1.69 – 2.41 | 0.468 | 0.113 | 0.207 – 0.729 | -0.247 | 0.717 | -1.90 – 1.41 |
| U.S. Route 26, Wemme | 2.07 | 0.063 | 1.94 – 2.20 | 0.337 | 0.072 | 0.190 – 0.484 | 1.48 | 0.434 | 0.591 – 2.37 |
| U.S. Route 30, Portland | 1.92 | 0.083 | 1.75 – 2.09 | 0.414 | 0.085 | 0.239 – 0.589 | 1.22 | 0.464 | 0.262 – 2.18 |
| Interstate I-5 Fremont Bridge, Portland | 2.23 | 0.111 | 2.00 – 2.46 | 0.566 | 0.082 | 0.397 – 0.735 | -0.357 | 0.456 | -1.30 – 0.582 |
| St. Johns Bridge, U.S. Route 30BY, Portland | 1.72 | 0.142 | 1.40 – 2.04 | 0.472 | 0.101 | 0.247 – 0.697 | -0.079 | 0.661 | -1.55 – 1.39 |
| Oregon U.S. Route 20, Corvallis | 1.43 | 0.054 | 1.32 – 1.54 | 0.275 | 0.068 | 0.135 – 0.415 | 1.69 | 0.456 | 0.751 – 2.63 |
| Median of sites | 1.99 | 0.086 | 1.81 – 2.17 | 0.441 | 0.068 | 0.301 – 0.581 | 0.571 | 0.456 | -0.368 – 1.51 |
| Lumped data | 1.91 | 0.045 | 1.82 – 2.00 | 0.51 | 0.033 | 0.445 – 0.575 | 0.296 | 0.216 | -0.131 – 0.723 |
| TP: phosphorus, water, unfiltered, mg/L (p00665) | | | | | | | | | |
| Oregon U.S. Route 20, Bend | -0.424 | 0.055 | -0.55 – -0.30 | 0.165 | 0.052 | 0.045 – 0.285 | 1.01 | 0.717 | -0.64 – 2.66 |
| U.S. Route 26, Wemme | -0.789 | 0.105 | -1.00 – -0.58 | 0.584 | 0.089 | 0.402 – 0.766 | -0.767 | 0.421 | -1.63 – 0.09 |
| U.S. Route 30, Portland | -0.679 | 0.064 | -0.81 – -0.55 | 0.294 | 0.058 | 0.173 – 0.415 | 0.914 | 0.501 | -0.13 – 1.96 |
| Interstate I-5 Fremont Bridge, Portland | -0.425 | 0.094 | -0.62 – -0.23 | 0.419 | 0.066 | 0.281 – 0.557 | -0.044 | 0.512 | -1.12 – 1.03 |
| Median of sites | -0.552 | 0.078 | -0.72 – -0.39 | 0.357 | 0.059 | 0.233 – 0.480 | 0.435 | 0.501 | -0.61 – 1.48 |
| Lumped data | -0.625 | 0.051 | -0.73 – -0.52 | 0.457 | 0.043 | 0.371 – 0.543 | -0.754 | 0.267 | -1.29 – -0.22 |
| TCu: copper, water, unfiltered, recoverable, µg/L (p01042) | | | | | | | | | |
| Oregon U.S. Route 20, Bend | 1.38 | 0.058 | 1.25 – 1.51 | 0.175 | 0.041 | 0.080 – 0.270 | -0.022 | 0.717 | -1.68 – 1.63 |
| U.S. Route 26, Wemme | 1.18 | 0.065 | 1.05 – 1.31 | 0.365 | 0.063 | 0.237 – 0.493 | -1.11 | 0.414 | -1.95 – -0.27 |
| U.S. Route 30, Portland | 1.37 | 0.057 | 1.25 – 1.49 | 0.285 | 0.041 | 0.200 – 0.370 | -0.247 | 0.464 | -1.21 – 0.71 |
| Interstate I-5 Fremont Bridge, Portland | 1.76 | 0.061 | 1.63 – 1.89 | 0.313 | 0.045 | 0.220 – 0.406 | -0.334 | 0.456 | -1.27 – 0.61 |
| St. Johns Bridge, U.S. Route 30BY, Portland | 1.49 | 0.057 | 1.36 – 1.62 | 0.180 | 0.04 | 0.090 – 0.270 | -0.068 | 0.687 | -1.62 – 1.49 |
| Oregon U.S. Route 20, Corvallis | 0.986 | 0.078 | 0.82 – 1.16 | 0.281 | 0.069 | 0.131 – 0.431 | 0.864 | 0.616 | -0.48 – 2.21 |
| Median of sites | 1.38 | 0.065 | 1.24 – 1.52 | 0.283 | 0.046 | 0.186 – 0.380 | -0.158 | 0.524 | -1.26 – 0.94 |
| Lumped data | 1.36 | 0.037 | 1.29 – 1.43 | 0.398 | 0.027 | 0.345 – 0.451 | -0.303 | 0.226 | -0.75 – 0.15 |
| SSC: suspended sediment concentration, mg/L (p80154); estimated from TSS | | | | | | | | | |
| Oregon U.S. Route 20, Bend | 2.29 | — | — | 0.717 | — | — | -0.677 | — | — |
| U.S. Route 26, Wemme | 2.36 | — | — | 0.462 | — | — | 1.48 | — | — |
| U.S. Route 30, Portland | 2.15 | — | — | 0.569 | — | — | 1.22 | — | — |
| Interstate I-5 Fremont Bridge, Portland | 2.57 | — | — | 0.778 | — | — | -0.357 | — | — |
| St. Johns Bridge, U.S. Route 30BY, Portland | 1.87 | — | — | 0.640 | — | — | -0.079 | — | — |
| Oregon U.S. Route 20, Corvallis | 1.48 | — | — | 0.378 | — | — | 1.69 | — | — |
| Median of sites | 2.22 | — | — | 0.605 | — | — | 0.571 | — | — |
| Lumped data | 2.13 | — | — | 0.689 | — | — | 0.409 | — | — |

A rank-correlation analysis using Spearman's rho for average annual daily traffic (AADT; table 15) and the average, standard deviation, and skew of the common (base 10) logarithms of event-mean concentrations in highway runoff guided the selection of representative statistics (table 16). Although there appears to be strong correlations between the AADT at the monitoring sites and the standard deviation and skew of TSS, and between the ADT at the monitoring sites and the average of TCu concentrations, the 95-percent confidence intervals for these Spearman's rho values cross zero, which means that the correlations are not statistically significant at the 95th percentile. Similarly, none of the correlations among the average, standard deviation, and skew of highway-runoff concentrations were significantly different from zero. Therefore, the median of each highway-runoff statistic (average, standard deviation, and skew) will be used to represent highway-runoff concentrations in the example simulations performed as part of this study.

## Developed-Area Runoff Quality

The quality of runoff from the developed areas was simulated by using EMC data from the September 2016 version of the International Best Management Practice (BMP) Database (www.bmpdatabase.org/) because developed-area runoff data in Oregon are limited. EMC data collected from BMP inflow-monitoring points in the International BMP Database represent stormwater from developed areas that is routed to the BMPs for treatment.

A simple replacement method was used to estimate statistics for sites with one or more values below the reported detection limits. The International BMP Database does not provide the means to calculate censored values by using statistical methods, but instead has a concentration field that has either an uncensored value or one-half the reported detection limit. Statistical methods for estimating sample statistics with censored values are preferable to substitution methods (Helsel and Hirsch 2002), but Antweiler and Taylor (2008) indicated that substituting concentrations equal to one-half the detection limit was sufficient for developing planning-level estimates for water-quality statistics. Croghan and Egeghy (2003) determined that substituting concentrations equal to the detection-limit concentration divided by the square root of two produced unbiased estimates up to censoring levels of about 50 percent. Therefore, the latter approach was used, and only datasets with censored values that were composed of less than or equal to 50 percent of the total values in the dataset were included for estimating sample statistics. Most datasets had no censored values; about 18 percent of TSS and TP datasets, and about 31 percent of TCu datasets had one or more censored values.

There are wide ranges in the site statistics for all five runoff-quality constituents (table 17). The maximum geometric mean is 370, 106, 75 and 29 times the minimum geometric mean for TSS, TP, TCu, and SSC, respectively. EMC statistics were grouped by land-use categories, but there are no clear relations between land-use category and the magnitude of the geometric means (fig. 6).

Statistics for the logarithms of SSC were estimated using regression relations with statistics for the logarithms of TSS because there were only 14 non-highway-runoff sites in the International BMP database with sufficient SSC data (table 17). The Kendal-Theil Robust Line program (Granato, 2006) was used to estimate the average, standard deviation, and skew of the logarithms of SSC from the associated TSS statistic values from the 14 sites with both TSS and SSC data (table 18). In this case, the statistics were used as the regression variables rather than the individual sample results (as with the highway-runoff data) so that information from all 113 sites with TSS data could be used to estimate SSC statistics. The estimated logarithmic SSC statistics are shown in table 17; the associated arithmetic statistics were not estimated because only the logarithmic statistics are used in runoff-quality simulations. Many of the estimated SSC statistics are less than the calculated statistics for the same exceedance frequency using the 14 sites (table 17). For example, the population of estimated geometric mean SSC values shown in figure 6*D* (the blue diamonds) are less than the calculated geometric mean SSC values (the black dots) at the same exceedance frequency. This is because the runoff monitoring sites that had both SSC and TSS data were among the sites with the highest TSS values. For example, the median of geometric means of TSS concentrations was 51 mg/L for all sites and 70.2 mg/L for the sites with SSC data (table 17). Similarly, the average of geometric means of TSS concentrations was 48 mg/L for all sites and 67 mg/L for the sites with SSC data.

The statistics listed in table 17 were ranked and selected independently. The averages, standard deviations, and skew values on each row in the table may be from different study sites. For example, the minimum SSC skew value may be from a different site than the site with the minimum SSC average value. To evaluate the validity of ranking and selection of the statistics independently, a rank-correlation analysis was done to assess potential relations among the average, standard deviation, and skew of the logarithms of EMC values. All of these variables were weakly correlated (defined herein as a rho value less than 0.5) for the other water-quality constituents (table 19). The lack of strong correlations among the three sample statistics supports the selection of these statistics from different sites.

**Table 16.** Rank-correlation coefficients (Spearman's rho) between average annual daily traffic and the average, standard deviation, and skew of the common (base 10) logarithms of event-mean concentrations in composite samples of highway and bridge-deck runoff collected in Oregon, 2008–16.

[Rho values for TP are in *italics* because a minumum of five values is needed to quantitatively estimate the rho value and only four values were available (see table 15; Abdel-Megeed, 1984). The values in parentheses are the 95-percent confidence intervals of rho, which were calculated by using Fisher's Z (Haan, 1977). If the 95-percent confidence interval spans a value of zero, then the rho value is not statistically different from zero. **Abbreviations:** TCu, total copper; TP, total phosphorus; TSS, total suspended sediment; AADT, Average annual daily traffic; mg/L milligram per liter]

| Six sites | AADT | Average | Standard deviation | Skew |
|---|---|---|---|---|
| TSS: solids, suspended, water, mg/L (p00600) | | | | |
| AADT | 1 | | | |
| Average | 0.43 (-0.79 – 0.96) | 1 | | |
| Standard deviation | 0.94 (-0.62 – 0.98) | 0.49 (-0.77 – 0.96) | 1 | |
| Skew | -0.83 (-0.97 – 0.66) | -0.6 (-0.97 – 0.74) | -0.94 (-0.98 – 0.62) | 1 |
| **Four sites** | **AADT** | **Average** | **Standard deviation** | **Skew** |
| TP: phosphorus, water, unfiltered, mg/L (p00665) | | | | |
| AADT | *1* | | | |
| Average | *0.4* | *1* | | |
| Standard deviation | *-0.2* | *-0.8* | *1* | |
| Skew | *0.2* | *0.8* | | *1* |
| **Six sites** | **AADT** | **Average** | **Standard deviation** | **Skew** |
| TCu: copper, water, unfiltered, recoverable, µg/L (p01042) | | | | |
| AADT | 1 | | | |
| Average | 0.943 (-0.62 – 0.98) | 1 | | |
| Standard deviation | 0.029 (-0.90 – 0.91) | -0.143 (-0.93 – 0.87) | 1 | |
| Skew | -0.371 (-0.95 – 0.81) | -0.257 (-0.94 – 0.84) | -0.829 (-0.97 – 0.66) | 1 |

**Table 17.** Event-mean concentration statistics for total suspended solids, total phosphorus, total copper, and suspended sediment concentrations in urban-runoff, from monitoring sites in Oregon.

[The pcodes are the U.S. Environmental Protection Agency parameter codes for each constituent. The runoff-quality statistics are from the September 2016 version of the International Best Management Practice Database (http://www.bmpdatabase.org/). **Skew:** coefficient of skewness, dimensionless. **Abbreviations:** TSS, total suspended solids; TCu, total copper; TP, total phosphorus; SSC, suspended sediment concentration; NE, not estimated; SD, standard deviation]

| Runoff-quality constituent | Fraction of censored values | Arithmetic statistics | | Skew | Geometric mean | Logarithmic (base 10) statistics | | Skew |
|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | | | Mean | SD | |
| TSS: solids, suspended, water, mg/L, p00530 (113 sites) | | | | | | | | |
| Minimum | 0.00 | 3.40 | 2.16 | 0.069 | 2.77 | 0.443 | 0.124 | -3.000 |
| 25th percentile | 0.00 | 38.2 | 30.4 | 1.037 | 26.9 | 1.430 | 0.301 | -0.362 |
| Median | 0.00 | 73.6 | 54.2 | 1.611 | 51.0 | 1.708 | 0.387 | -0.026 |
| 75th percentile | 0.00 | 129 | 127 | 2.481 | 90.0 | 1.954 | 0.462 | 0.340 |
| Maximum | 0.48 | 1,217 | 1,695 | 4.988 | 1,026 | 3.011 | 0.800 | 1.325 |
| TP: phosphorus, water, unfiltered, mg/L, p00665 (TP, 95 sites) | | | | | | | | |
| Minimum | 0.00 | 0.032 | 0.015 | -0.087 | 0.029 | -1.532 | 0.147 | -2.681 |
| 25th percentile | 0.00 | 0.126 | 0.088 | 0.945 | 0.095 | -1.021 | 0.240 | -0.282 |
| Median | 0.00 | 0.223 | 0.173 | 1.52 | 0.159 | -0.799 | 0.295 | 0.330 |
| 75th percentile | 0.00 | 0.418 | 0.302 | 2.69 | 0.279 | -0.554 | 0.360 | 0.744 |
| Maximum | 0.50 | 3.55 | 7.27 | 5.52 | 3.09 | 0.490 | 0.777 | 3.334 |
| TCu: copper, water, unfiltered, recoverable, μg/L, p01042 (TCu, 71 sites) | | | | | | | | |
| Minimum | 0.00 | 1.88 | 1.01 | -0.095 | 1.66 | 0.219 | 0.133 | -1.669 |
| 25th percentile | 0.00 | 8.04 | 4.65 | 0.793 | 6.30 | 0.799 | 0.215 | -0.229 |
| Median | 0.00 | 12.9 | 8.84 | 1.48 | 10.45 | 1.019 | 0.282 | 0.066 |
| 75th percentile | 0.05 | 22.2 | 18.9 | 2.30 | 15.9 | 1.203 | 0.359 | 0.688 |
| Maximum | 0.50 | 198 | 874 | 4.58 | 124 | 2.094 | 0.872 | 3.880 |
| SSC: suspended sediment concentration, mg/L, p80154 (SSC, 14 sites) | | | | | | | | |
| Minimum | 0.00 | 24.1 | 20.8 | 0.707 | 16.6 | 1.221 | 0.261 | -0.685 |
| 25th percentile | 0.00 | 81.2 | 81.5 | 1.111 | 50.8 | 1.706 | 0.364 | -0.193 |
| Median | 0.00 | 146 | 123 | 1.477 | 105 | 2.022 | 0.434 | 0.207 |
| 75th percentile | 0.00 | 492 | 539 | 2.494 | 157 | 2.195 | 0.529 | 0.725 |
| Maximum | 0.00 | 1,131 | 1,877 | 4.098 | 484 | 2.685 | 0.632 | 1.054 |
| SSC: suspended sediment concentration, mg/L, p80154; estimated from TSS (SSC, 113 sites) | | | | | | | | |
| Minimum | NE | NE | NE | NE | 2.63 | 0.420 | 0.163 | -2.476 |
| 25th percentile | NE | NE | NE | NE | 34.1 | 1.533 | 0.311 | -0.153 |
| Median | NE | NE | NE | NE | 70.2 | 1.847 | 0.382 | 0.143 |
| 75th percentile | NE | NE | NE | NE | 133 | 2.124 | 0.445 | 0.465 |
| Maximum | NE | NE | NE | NE | 2,069 | 3.316 | 0.726 | 1.332 |

**Table 18.** Regression relations to estimate logarithmic suspended-solids concentration statistics from logarithmic total-suspended solids statistics in urban-runoff.

[Regression equations developed by using the Kendal Theil Robust Line (Granato, 2006)]

| Logarithmic statistics | Rank correlation | Intercept | Slope | Root mean square error |
|---|---|---|---|---|
| Average | 0.845 | -0.079 | 1.127 | 0.202 |
| Standard deviation | 0.763 | 0.060 | 0.833 | 0.084 |
| Skew coefficient | 0.607 | 0.165 | 0.881 | 0.454 |

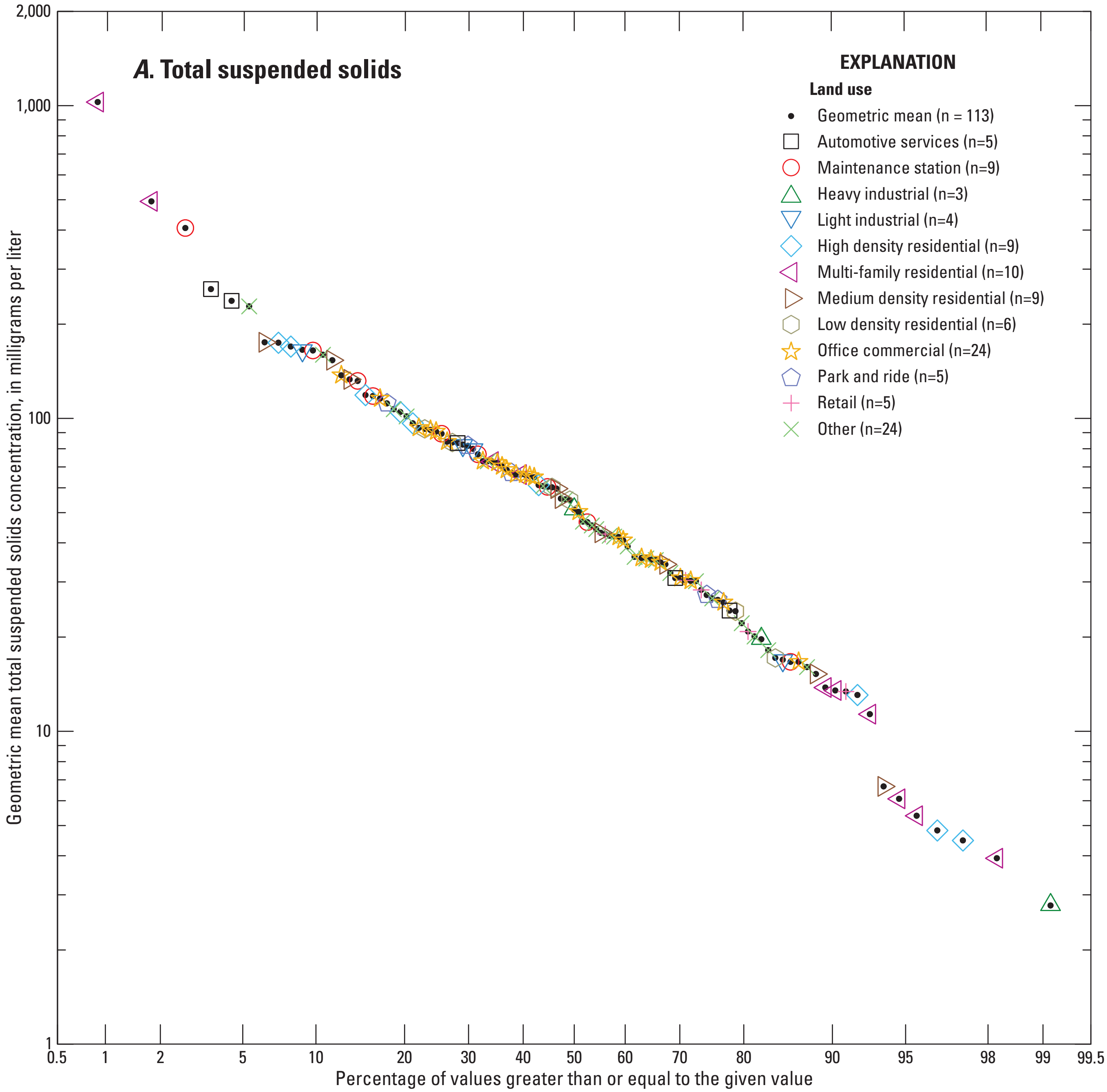



**Figure 6.** Distribution of the geometric means of (*A*) total suspended solids, (*B*) total phosphorus, (*C*) total copper, and (*D*) suspended sediment concentrations in urban runoff from non-highway land-use sites.

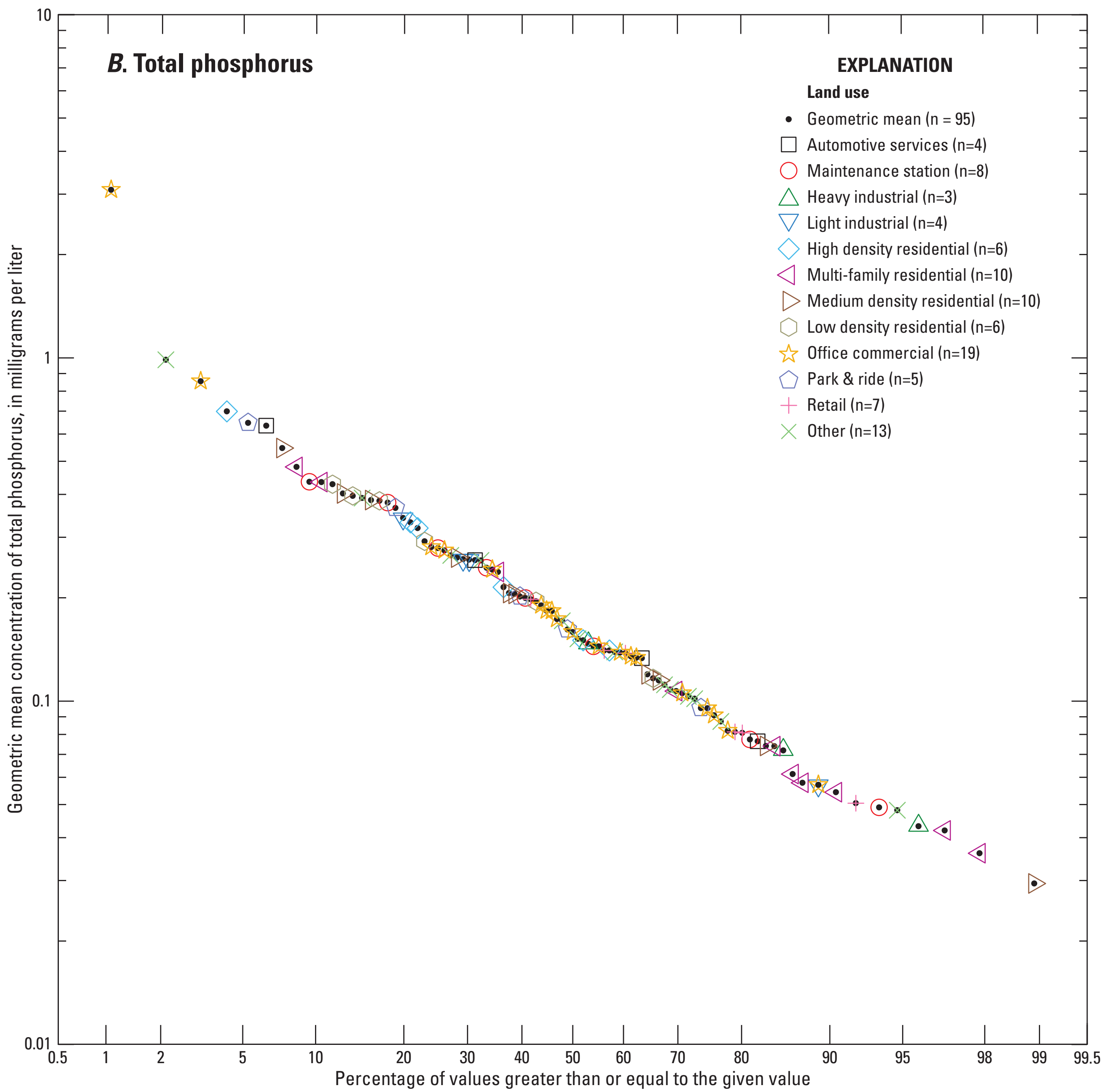



**Figure 6.—Continued**

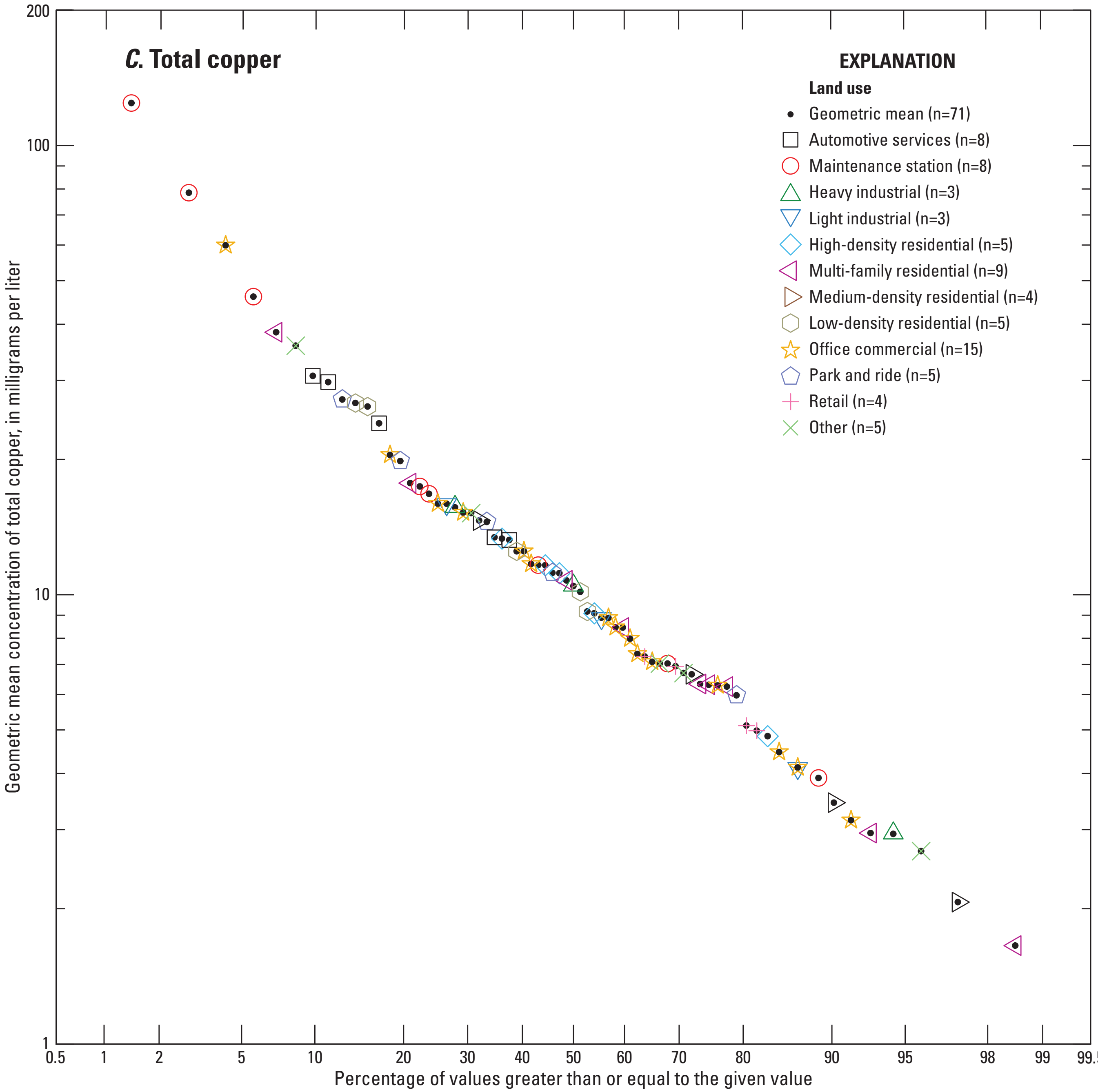



**Figure 6.—Continued**

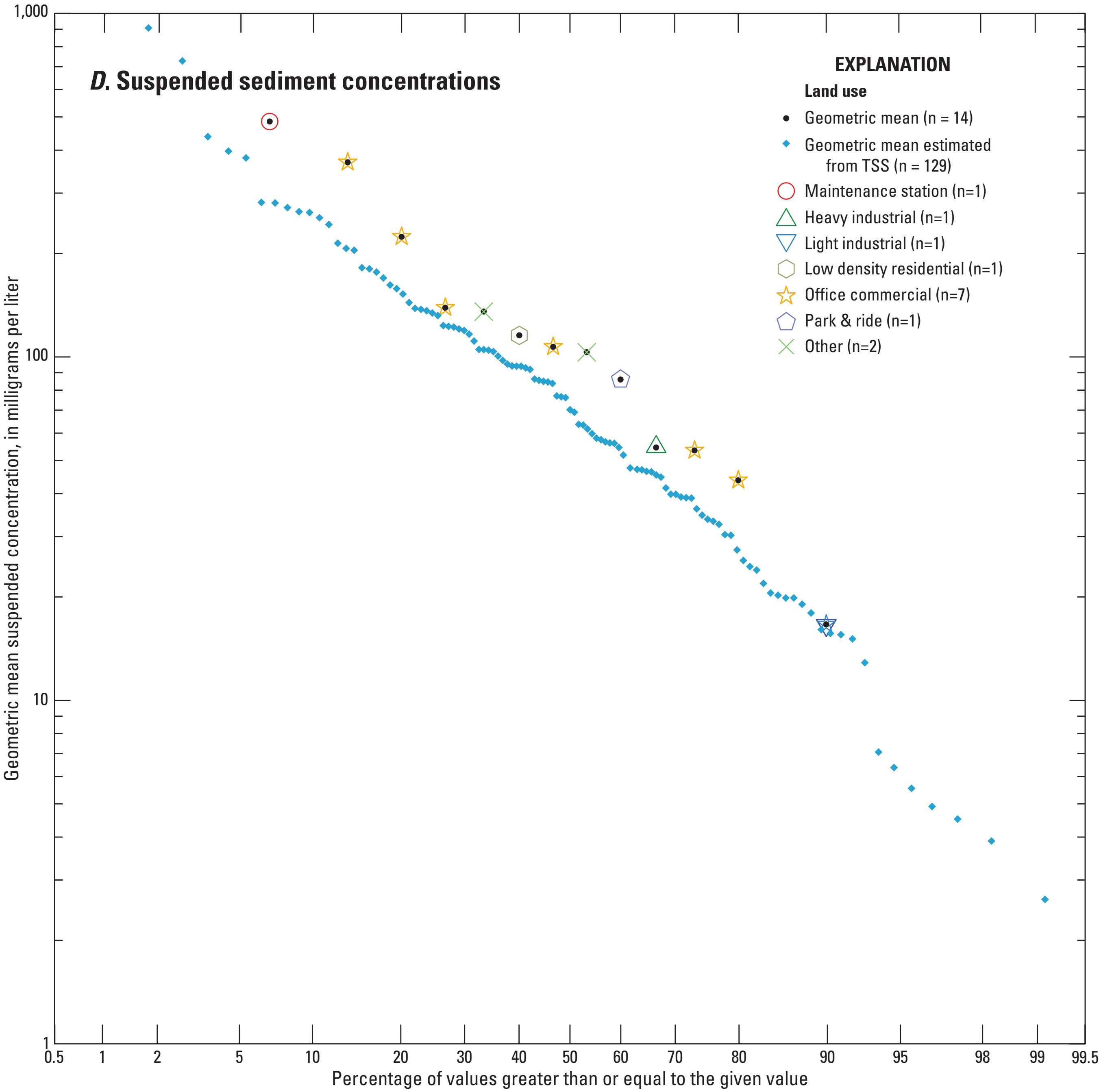



**Figure 6.—Continued**

**Table 19.** Rank correlation coefficients among water-quality concentration statistics.

[**SD:** Standard deviation. **Skew:** Coefficient of skewness, dimensionless. The runoff-quality statistics arye from the September 2016 version of the International Best Management Practice Database (http://www.bmpdatabase.org/). Rank correlations are for the statistics calculated by using the common-logarithms of event mean concentrations. **Abbreviations**: mg/L, milligrams per liter; µg/L, micrograms per liter]

| | Mean | SD | Skew |
|---|---|---|---|
| Solids, suspended, water, mg/L, p00530 (113 sites) | | | |
| Mean | 1 | 0.016 | -0.105 |
| SD | 0.016 | 1 | -0.059 |
| Skew | -0.105 | -0.059 | 1 |
| Phosphorus, water, unfiltered, mg/L, p00665 (95 sites) | | | |
| Mean | 1 | -0.166 | -0.180 |
| SD | -0.166 | 1 | 0.103 |
| Skew | -0.180 | 0.103 | 1 |
| Copper, water, unfiltered, recoverable, µg/L, p01042 (71 sites) | | | |
| Mean | 1 | -0.000 | -0.028 |
| SD | -0.000 | 1 | -0.128 |
| Skew | -0.028 | -0.128 | 1 |
| Suspended sediment concentration, mg/L, p80154 (14 sites) | | | |
| Mean | 1 | 0.300 | 0.176 |
| SD | 0.300 | 1 | 0.344 |
| Skew | 0.176 | 0.344 | 1 |

The lognormal distribution commonly is used to characterize and simulate urban-runoff quality (Athayde and others, 1983; Di Toro, 1984; Driscoll and others, 1990; Van Buren and others, 1997; Novotny, 2004; National Research Council, 2009). EMCs may be simulated as lognormal values by using a logarithmic skew of zero. In this study, only 12, 24, 17, and 7 percent of skew values are outside the 95-percent confidence limits of a zero skew value for TSS, TP, TCu, and SSC, respectively. Use of zero skew also may be warranted because skew values were only weakly correlated with the average and standard deviation of the logarithms of EMCs for any of the five constituents (table 19).

Runoff quality for the developed land-use areas was simulated with the assumption that these constituents could be modeled by using lognormal distribution. Therefore, selected values of the average, standard deviation, and skew of the logarithms of EMCs were used to simulate runoff quality (table 17). The 75th percentile of site statistics was used to simulate the quality of stormwater runoff from developed areas identified and delineated within each watershed of interest by using StreamStats (U.S. Geological Survey, 2018). For example, when simulating the runoff quality of TP from developed land, the logarithms of the average, standard deviation, and skew were set to -0.5541, 0.3601, and 0.7436, respectively. The selected values of the average, standard deviation and skew rather than land-use specific values are representative because the developed land-cover categories in StreamStats represent many developed land-use types.

## Water-Quality Transport Curve Analysis

The quality of stormflows from the basin upstream from the highway or developed-area outfalls was simulated using water-quality transport curves developed from USGS data from hydrologically similar sites. A water-quality transport curve is a regression relation between stormflow volumes and constituent concentrations (Granato, 2006, 2013; Granato and others, 2009). SELDM uses the regression relation to calculate a most-probable value for the concentration for a given stormflow and uses a random variate with the median absolute deviation of residuals to generate a concentration value above and below the line to recreate both the relation and the scatter in the original dataset. Loading from sources such as wastewater treatment plants, fertilizer applications, agricultural underdrains, septic-system effluent, other commercial or industrial sources, or natural geologic sources were not considered in the development of any transport curves.

At Bear and Mill Creeks, transport curves for SSC and TP were developed using regional data from nearby stations with similar drainage areas and basin characteristics that were indicative of largely undeveloped watersheds (table 20, fig. 7).

Developing transport curves for the sites in the Bear Creek watersheds was less straightforward. The three long-term streamgages within the Bear Creek watershed indicate low streamflow productivity at those sites (table 11). In other words, the cubic-feet per second per square mile of drainage area [$(ft^3/s)/mi^2$] values are much lower than what is measured at neighboring stations. With such low streamflow productivity, using a transport curve without adjustments results in unrealistically low levels of background constituent concentrations, as the $(ft^3/s)/mi^2$ values are clustered around left side of the curve representing low streamflow. For example, the transport curve for TP has a slope of zero for all streamflow values less than 9.18 $(ft^3/s)/mi^2$ (fig. 7). At the Emigrant Creek at Highway 66 site, 6.6 percent of all the simulated concurrent upstream stormflows exceeded this threshold, so using an unadjusted transport curve would result in very few TP EMCs elevated above the segment of the transport curve with no slope. By comparison, with the regional data used to develop the transport curve, 11.4 percent of the streamflows exceeded that same threshold.

Initial model runs at Bear Creek used transport curves that were not adjusted, and the resulting water-quality constituent EMCs were deemed unreasonably low to use. This type of adjustment was warranted because the inflection point on the water-quality transport curve is indicative of the threshold where runoff carries the runoff constituents to the stream and provides the energy to keep the runoff constituents flowing. The transport curves were selected to represent background rather than developed conditions. In a natural system, the stream and the channel will reach a dynamic equilibrium and the size and composition of the channel will reflect the flow energy in the stream (Leopold and others, 1964). Therefore, sediment transport is likely to occur at lower $(ft^3/s)/mi^2$ values in Bear Creek than at the data-collection (regional) sites because the cross-section of flow in Bear Creek would be smaller than for more productive streams at sites with the same drainage areas; thus, the transport curve warranted adjustment to reflect the transport capacity within the stream channel. This indicates the limitation in the assumption of hydrologic similarity between sites at which the data are available as well as the conditions prevalent in Bear Creek and the need for more background water-quality data at more sites in Oregon streams.

To account for the low productivity in the Bear Creek watershed, individual transport curves were developed for each site by scaling the inflection and end points of each transport curve in relation to the streamflow distribution of the site. For example, the regional data used to develop the initial TP transport curve resulted at an inflection point at 9.18 $(ft^3/s)/mi^2$on the x-axis and 0.028 mg/L on the y-axis (fig. 7). Approximately 11.4 percent of the streamflows from the regional dataset were greater than 9.18 $(ft^3/s)/mi^2$, and would thus plot to the right of this inflection point on the portion of the transport curve with the positive slope. At the Emigrant Creek at Highway 66 site, that inflection point was moved from 9.18 to 2.77 $(ft^3/s)/mi^2$. With this newly scaled transport curve, 11.4 percent of streamflows for the Emigrant Creek at Highway 66 site were greater than the new inflection point of 2.77 $(ft^3/s)/mi^2$, which is the same percentage of exceedances derived for the original transport curve using the regional sites. The end point on the right of the transport curve was scaled using the same method [72.7–46.8 $(ft^3/s)/mi^2$]. Figure 8 illustrates the example outlined here. All values are plotted in log-10 space in figure 8.

## Dependent Water-Quality Analysis

Concentrations of TCu in stormflows from the receiving water basin upstream from the highway or developed-area outfalls were simulated by using dependent water-quality relations. In SELDM, a dependent water-quality relation is used to estimate concentrations for one constituent from another (Granato, 2013). As with the transport curve, the dependent relation takes the form of a regression relation with a random-error component:

$$Yi_i = m * X_i + b + e^i \; for \; i = 1 \text{ to } n \tag{5}$$

where

- $X_i$ is the explanatory variable for each datum ($i$);
- $Y_i$ is the dependent variable for each datum ($i$);
- $e_i$ is the residual error or uncertainty in the predicted Y value for each datum ($i$);
- $m$ is the estimated slope;
- $b$ is the estimated intercept; and
- $n$ is the number of $XY$ data in the sample.

In this study, a relation between suspended sediment, which is a commonly measured constituent in streamflow, and TCu was developed because of a paucity of TCu data available for stormflows in Oregon. Although equation 5 resembles a regression equation, it was developed by using a three-step process. In this low-development scenario, it is assumed that geologic sources are a primary source of TCu. Therefore, the first step was to estimate SSC, the second step was to estimate particulate copper concentrations, and the third step was to estimate TCu concentrations.

The previously developed water-quality transport curve for estimating SSC in Mill Creek was used to generate concurrent upstream stormflow SSC and streamflow data. Figure 9 shows the data used to develop the SSC transport curve (a three-segment water-quality transport curve) and a simulated population of SSC.

**Table 20.** U.S. Geological used to develop water-quality transport curves for Bear and Mill Creeks, Oregon.

[**Lattitude and Longitude:** In decimal degrees North and West, respectively. **Mean over POR:** Mean over entire period of record (POR). Statistic was calculated using daily value (U.S. Geological Survey (2017); (ft3/s)/mi2, cubic feet per second per square mile of drainage area. **Abbreviations:** SSC, suspended-sediment concentration; TP, total phosphorus; mi$^2$, square mile; NLCD, National Land Cover Database; LC11FORSHB, Percentage of forests and shrub lands, classes 41 to 52, from NLCD (2011); LC11IMP, Mean percentage of impervious area determined from NLCD (2011; http://www.mrlc.gov/nlcd11_data.php) impervious dataset; LC11DEVH, Percentage of area developed, high intensity, NLCD (2011) class 24, (ft$^3$/s)/mi$^2$, cubic feet per second per square mile of drainage area; n/a, no streamflow data available for this site]

| USGS station ID | Station name | Lattitude | Longitude | Number of SSC samples | Number of TP samples | Drainage area (mi$^2$) | Percentage forest area (LC11FORSHB) | Percentage impervious area (LC11IMP) | Percentage urban area (LC11DEVHI) | Mean over period of record [(ft$_3$/s)/mi$_2$] |
|---|---|---|---|---|---|---|---|---|---|---|
| 14138900 | North Fork Bull Run River near Multnomah Falls, OR | 45.494 | -122.036 | 0 | 13 | 8.37 | 97 | 0.026 | 0 | 8.95 |
| 14139800 | South Fork Bull Run River near Bull Run, OR | 45.445 | -122.110 | 253 | 0 | 15.7 | 100 | 0.010 | 0 | 7.32 |
| 14158850 | Mckenzie River below Trail Br Dam near Belknap Springs, OR | 44.268 | -122.050 | 0 | 17 | 185 | 88 | 0.093 | 0 | 5.48 |
| 14159000 | Mckenzie River at Mckenzie Bridge, OR | 44.179 | -122.130 | 0 | 17 | 349 | 87 | 0.068 | 0 | 4.83 |
| 14162500 | Mckenzie River near Vida, OR | 44.268 | -122.050 | 0 | 18 | 185 | 92 | 0.053 | 0 | 4.36 |
| 14179100 | French Creek near Detroit, OR | 44.760 | -122.168 | 20 | 0 | 9.9 | 100 | 0.12 | 0 | 7.23 |
| 14181900 | Little N Santiam River Abv Evans Creek, at Elkhorn, OR | 44.836 | -122.355 | 21 | 0 | 53.1 | 100 | 0.035 | 0 | n/a |
| 14185000 | South Santiam River Below Cascadia, OR | 44.392 | -122.498 | 27 | 0 | 174 | 96 | 0.075 | 0 | 4.57 |
| 14185800 | Middle Santiam R near Cascadia, OR | 44.515 | -122.372 | 26 | 0 | 104 | 99 | 0.048 | 0 | n/a |
| 14200400 | Little Abiqua Creek near Scotts Mills, OR | 44.956 | -122.628 | 94 | 76 | 9.81 | 92 | 0.032 | 0 | 3.28 |
| 14203750 | Gales Creek near Glenwood, OR | 45.643 | -123.370 | 23 | 18 | 7.3 | 86 | 0.29 | 0 | 4.51 |
| 14205400 | East Fork Dairy Creek near Meacham Corner, OR | 45.682 | -123.070 | 26 | 23 | 33.8 | 90 | 0.24 | 0 | 2.60 |
| 14211000 | Clackamas River near Clackamas, OR | 45.393 | -122.533 | 20 | 0 | 933 | 87 | 0.7 | 0 | 2.95 |
| 14301000 | Nehalem River near Foss, OR | 45.704 | -123.755 | 0 | 132 | 673 | 87 | 0.49 | 0 | 3.79 |
| 14306500 | Alsea River near Tidewater, OR | 44.386 | -123.832 | 42 | 44 | 334 | 88 | 0.43 | 0 | 4.14 |
| 14307620 | Siuslaw River near Mapleton, OR | 44.062 | -123.883 | 0 | 70 | 591 | 88 | 0.32 | 0 | 3.35 |

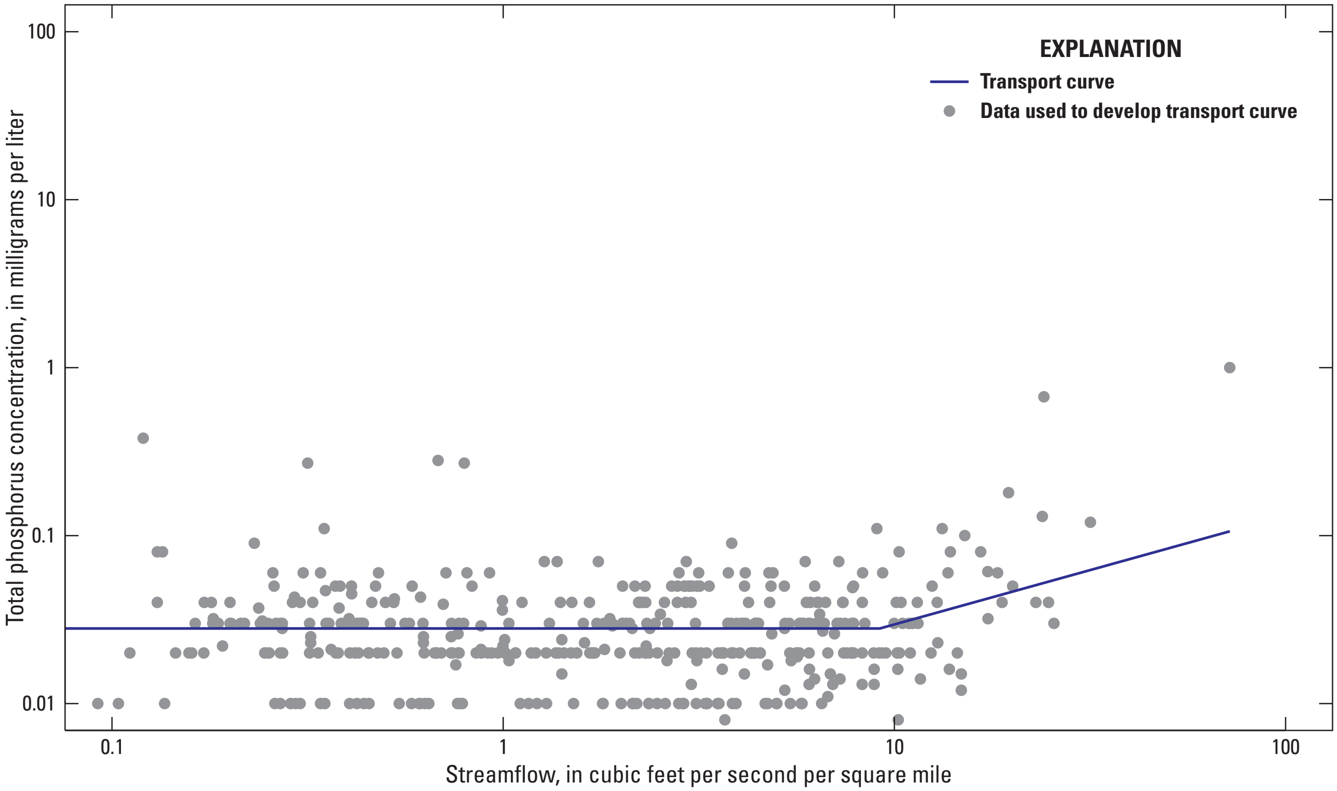



**Figure 7.** Relation between streamflow and total phosphorus in largely undeveloped basins in Oregon.

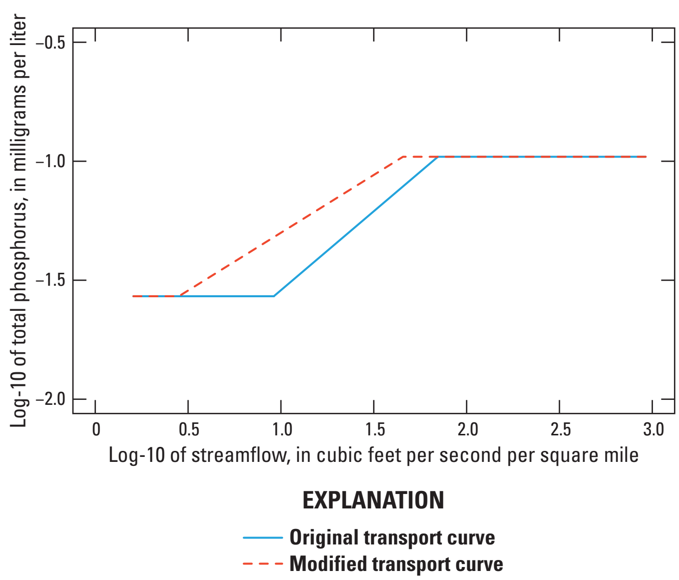



**Figure 8.** Development of the total phosphorus transport curve for the Emigrant Creek at Highway 66 site, Oregon.

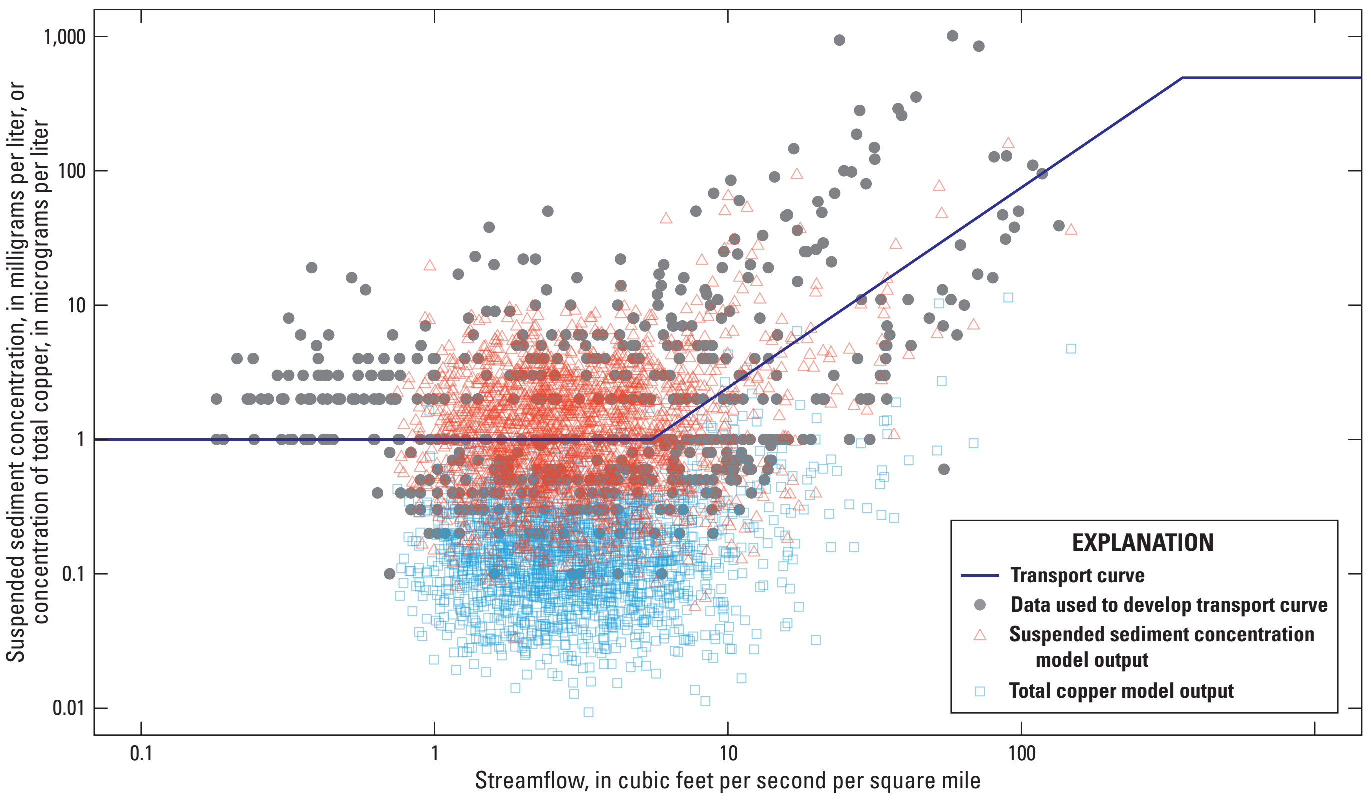



**Figure 9.** Relation between streamflow, suspended-sediment concentration, and total copper at Mill Creek at Mission Street, Oregon.

Concentrations of particulate copper (PCu) in the suspended sediment were estimated using bed-sediment copper concentration data compiled by Horowitz and Stephens (2008). Copper concentration statistics for the simulation were estimated using data from 16 samples collected in minimally developed watersheds in the Willamette Valley in Oregon. A population density of less than about 60 people per mi$^2$ (equivalent to value of about 1 percent) was set as the threshold for qualifying as 'minimally developed.'

The average and standard deviation of the PCu concentrations of the 16 Willamette sites were 0.050 and 0.022 micrograms (µg) of Cu per milligram (mg) of sediment, respectively. The average (-1.334) and standard deviation (0.1721) of the logarithms of these PCu concentrations were used to simulate particulate concentrations in the water column as a function of the simulated SSC (fig. 10). The slope of the logarithm of PCu concentration is one because it is calculated as the mass of copper per unit mass of sediment. The final equation for calculating PCu was:

$$PCu = 10^{(-1.334)+\log10(SSC)+0.172*K_i} \qquad (6)$$

where

PCu is particulate-copper concentration, in micrograms per liter,

SSC is suspended-sediment concentration, in milligrams per liter, and

$K_i$ is a random variable with a mean of zero and a standard deviation of 1, which is unitless.

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

The remaining procedure used to estimate TCu follows methods described by Granato and Jones (2016). Logarithmic slopes and intercepts of the $K_d$ equation calculated from the Pelletier's (1996) copper equation were used to estimate values of $K_d$

$$K_d = 577{,}068 * \text{SSC}^{-0.617} * 1.77^{Z_{random}} \quad (7)$$

where

$K_d$ is the ratio of particulate to dissolved metal in a water column,

SSC is suspended-sediment concentration, in milligrams per liter, and

$Z_{random}$ is a random variable with a mean of zero and a standard deviation of 1, which is unitless.

Once the values of the $K_d$ are estimated, TCu concentrations can be estimated using the theoretical relation with PCu:

$$\text{TCu} = \text{PCu}\left(1 + \frac{10^6}{K_d * \text{SSC}}\right) \quad (8)$$

where

TCu is total copper concentration, in micrograms per liter.

PCu is particulate copper concentration, in micrograms per liter

$K_d$ is the ratio of particulate to dissolved metal in a water column, in liters per kilogram, and

SSC is suspended-sediment concentration, in milligrams per liter,.

The SSC, PCu, and $K_d$ variables are stochastically generated with deterministic and random components. Consequently, equation 8 cannot be modeled in SELDM. The R programming language (https://www.r-project.org/) was used to perform Monte Carlo simulations to estimate TCu values as a dependent variable from SSC, PCu, and $K_d$. The modeled data were used to develop a logarithmic relation between SSC and TCu (fig. 10).

The resulting relation is a simplification, and this relation models TCu values best near median levels of SSC and deviates further as SSC values move closer to the extremes on either end. These equations provide planning-level estimates that are well within the uncertainty of the processes for using SSC and the concentrations of copper on sediment from hydrologically similar basins to the site of interest and using literature-based distribution coefficients to calculate TCu from PCu. Simulated TCu concentrations, however, were well within expected tolerances at concentrations of concern for the current study. The final concurrent upstream stormflow relation between SSC and TCu was used to generate background TCu EMCs for no-development upstream scenarios and can be considered as background EMCs upon which copper from other sources may be superimposed.

The resulting EMC statistics derived for upstream flow concentrations for all simulation scenarios using upstream random distributions, upstream transport curve, and upstream dependent curves are listed in table 21. Only the logarithmic base 10 statistics are included, as the other statistics are not used by SELDM for calculations.

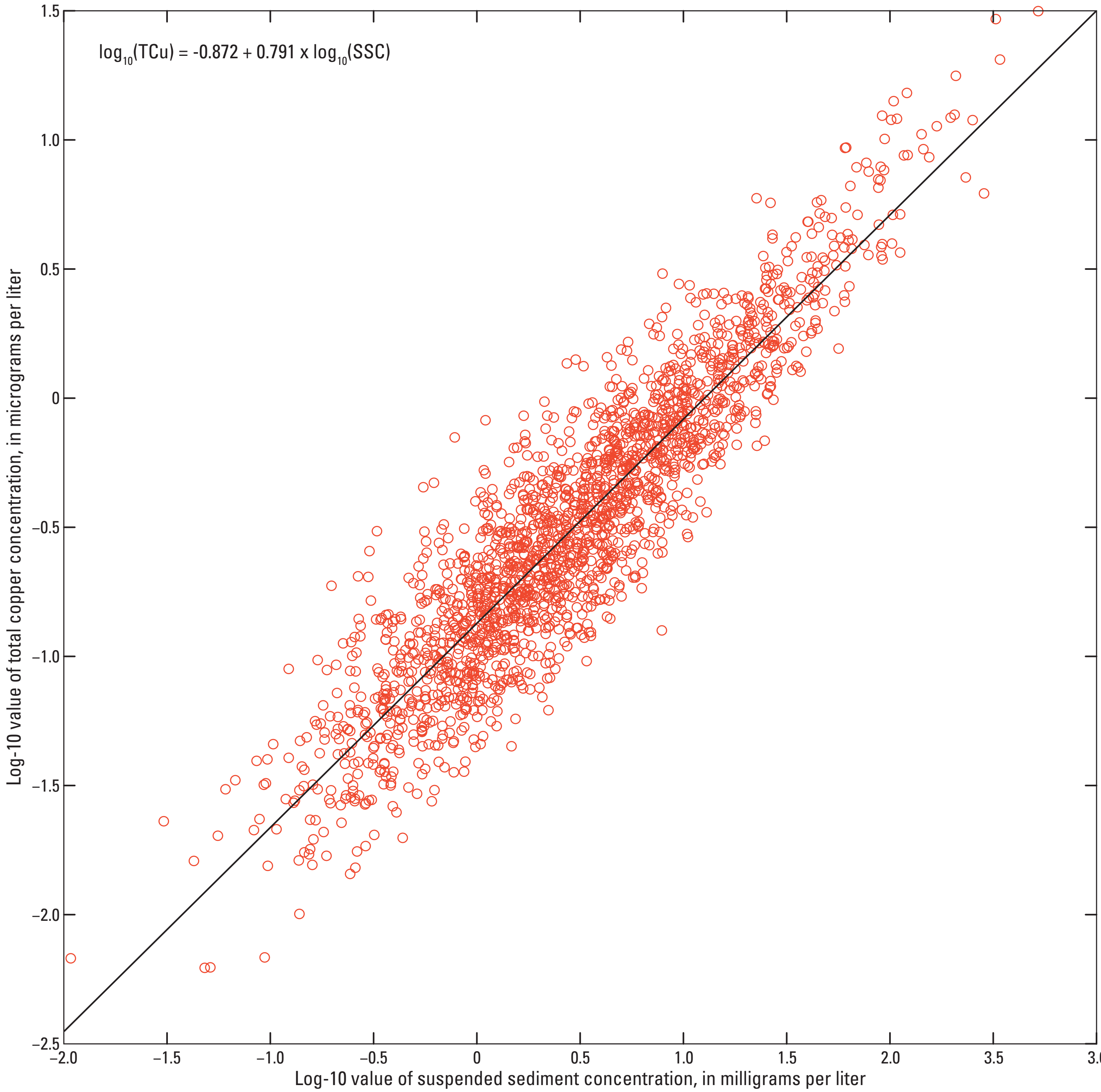



**Figure 10.** Modeled relation between suspended sediment concentration (SSC) and total copper concentration (TCu).

**Table 21.** Event-mean concentration statistics for total phosphorus, total copper, and suspended sediment concentrations in upstream streamflow.

[**Skew:** coefficient of skewness, dimensionless. The p codes are the U.S. Environmental Protection Agency parameter codes for each constituent. **Abbreviations:** MAD, median absolute deviation; MaxQ, maximum streamflow values used for this line; mg/L, milligram per liter; µg/L, micrograms per liter; SD, standard deviation –, not calculated]

| Simulation scenarios with upstream random distributions | | | | |
|---|---|---|---|---|
| Simulation scenario | Site | Logarithmic (base 10) statistics | | |
| | | Average | SD | Skew |
| Phosphorus, water, unfiltered, milligrams per liter, p00665 | | | | |
| 2B - (Upstream Developed + Upstream Undeveloped) + Highway | Emmigrant Creek at Highway 66 | -1.220 | 0.294 | 1.097 |
| | Emigrant Creek at Ashland | -1.232 | 0.258 | 1.016 |
| | Hamilton Creek at Ashland | -0.719 | 0.350 | 0.730 |
| | Bear Creek at Talent | -1.125 | 0.293 | 0.983 |
| | Bear Creek at Phoenix | -1.083 | 0.300 | 0.943 |
| | Bear Creek at I-5 | -1.029 | 0.317 | 0.906 |
| | Bear Creek at Kirtland Road | -0.926 | 0.334 | 0.823 |
| 2B - (Upstream Developed + Upstream Undeveloped) + Highway | Mill Creek at Boedigheimer Road | -1.425 | 0.206 | 0.407 |
| | Mill Creek at Stayton | -1.421 | 0.197 | 0.456 |
| | Mill Creek at Aumsville | -1.090 | 0.319 | 0.980 |
| | Mill Creek at Mill Creek Road | -1.083 | 0.323 | 0.949 |
| | Mill Creek at Turner | -1.076 | 0.329 | 0.984 |
| | Mill Creek at I-5 | -1.011 | 0.338 | 0.866 |
| | Mill Creek at Mission Street | -0.947 | 0.347 | 0.797 |
| Copper, water, unfiltered, recoverable, µg/L, p01042 | | | | |
| 2B - (Upstream Developed + Upstream Undeveloped) + Highway | Emmigrant Creek at Highway 66 | 0.189 | 0.379 | 0.460 |
| | Emigrant Creek at Ashland | 0.206 | 0.338 | 0.564 |
| | Hamilton Creek at Ashland | 0.843 | 0.290 | 0.142 |
| | Bear Creek at Talent | 0.356 | 0.332 | 0.451 |
| | Bear Creek at Phoenix | 0.425 | 0.334 | 0.258 |
| | Bear Creek at I-5 | 0.466 | 0.318 | 0.216 |
| | Bear Creek at Kirtland Road | 0.596 | 0.320 | 0.190 |
| 2B - (Upstream Developed + Upstream Undeveloped) + Highway | Mill Creek at Boedigheimer Road | -0.386 | 0.453 | 0.338 |
| | Mill Creek at Stayton | -0.339 | 0.416 | 0.409 |
| | Mill Creek at Aumsville | 0.305 | 0.407 | 0.110 |
| | Mill Creek at Mill Creek Road | 0.309 | 0.407 | 0.115 |
| | Mill Creek at Turner | 0.323 | 0.398 | -0.033 |
| | Mill Creek at I-5 | 0.418 | 0.388 | -0.015 |
| | Mill Creek at Mission Street | 0.511 | 0.377 | -0.055 |
| Suspended sediment concentration, mg/L, p80154 | | | | |
| 2B - (Upstream Developed + Upstream Undeveloped) + Highway | Emmigrant Creek at Highway 66 | 1.099 | 0.434 | 0.571 |
| | Emigrant Creek at Ashland | 1.148 | 0.397 | 0.67 |
| | Hamilton Creek at Ashland | 1.699 | 0.365 | 0.299 |
| | Bear Creek at Talent | 1.282 | 0.399 | 0.499 |
| | Bear Creek at Phoenix | 1.356 | 0.414 | 0.572 |
| | Bear Creek at I-5 | 1.366 | 0.397 | 0.314 |
| | Bear Creek at Kirtland Road | 1.477 | 0.389 | 0.265 |
| 2B - (Upstream Developed + Upstream Undeveloped) + Highway | Mill Creek at Boedigheimer Road | 0.590 | 0.560 | 0.361 |
| | Mill Creek at Stayton | 0.613 | 0.503 | 0.478 |
| | Mill Creek at Aumsville | 1.177 | 0.446 | 0.140 |
| | Mill Creek at Mill Creek Road | 1.162 | 0.45 | 0.189 |
| | Mill Creek at Turner | 1.174 | 0.465 | 0.138 |
| | Mill Creek at I-5 | 1.256 | 0.450 | 0.168 |
| | Mill Creek at Mission Street | 1.348 | 0.443 | 0.153 |

**Table 21.** Event-mean concentration statistics for total phosphorus, total copper, and suspended sediment concentrations in upstream streamflow.—Continued

| Simulation scenario | Site(s) | Curve 1 log10 values | | | | Curve 2 log10 values | | | | Curve 3 log10 values | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Intercept | Slope | MAD | MaxQ | Intercept | Slope | MAD | MaxQ | Intercept | Slope | MAD | MaxQ |
| **Simulation scenarios with upstream transport curves** | | | | | | | | | | | | | |
| Phosphorus, water, unfiltered, mg/L, p00665 | | | | | | | | | | | | | |
| All scenarios except 2B | Emmigrant Creek at Highway 66 | -1.553 | 0 | 0.146 | 0.443 | -1.763 | 0.473 | 0.199 | 1.671 | – | – | – | – |
| | Emigrant Creek at Ashland | -1.553 | 0 | 0.146 | 0.405 | -1.725 | 0.426 | 0.199 | 1.771 | – | – | – | – |
| | Hamilton Creek at Ashland | -1.553 | 0 | 0.146 | 0.484 | -1.691 | 0.285 | 0.199 | 2.522 | – | – | – | – |
| | Bear Creek at Talent | -1.553 | 0 | 0.146 | 0.400 | -1.731 | 0.444 | 0.199 | 1.710 | – | – | – | – |
| | Bear Creek at Phoenix | -1.553 | 0 | 0.146 | 0.389 | -1.768 | 0.552 | 0.199 | 1.443 | – | – | – | – |
| | Bear Creek at I-5 | -1.553 | 0 | 0.146 | 0.391 | -1.732 | 0.459 | 0.199 | 1.658 | – | – | – | – |
| | Bear Creek at Kirtland Road | -1.553 | 0 | 0.146 | 0.381 | -1.732 | 0.470 | 0.199 | 1.617 | – | – | – | – |
| All scenarios except 2B | All Mill Creek Sites | -1.553 | 0 | 0.146 | 0.963 | -2.176 | 0.647 | 0.199 | 1.862 | – | – | – | – |
| Suspended sediment concentration, mg/L, p80154 | | | | | | | | | | | | | |
| All scenarios except 2B | Emmigrant Creek at Highway 66 | 0.380 | 0.872 | 0.220 | 0.285 | 0.157 | 1.656 | 0.269 | 1.827 | 1.827 | 0 | 0.184 | 6 |
| | Emigrant Creek at Ashland | 0.380 | 0.721 | 0.220 | 0.344 | 0.020 | 1.768 | 0.269 | 1.789 | 1.789 | 0 | 0.184 | 6 |
| | Hamilton Creek at Ashland | 0.380 | 0.834 | 0.220 | 0.298 | 0.300 | 1.104 | 0.269 | 2.612 | 2.612 | 0 | 0.184 | 6 |
| | Bear Creek at Talent | 0.380 | 0.872 | 0.220 | 0.285 | 0.137 | 1.728 | 0.269 | 1.764 | 1.764 | 0 | 0.184 | 6 |
| | Bear Creek at Phoenix | 0.380 | 0.893 | 0.220 | 0.278 | 0.035 | 2.132 | 0.269 | 1.476 | 1.476 | 0 | 0.184 | 6 |
| | Bear Creek at I-5 | 0.380 | 0.891 | 0.220 | 0.279 | 0.131 | 1.785 | 0.269 | 1.71 | 1.71 | 0 | 0.184 | 6 |
| | Bear Creek at Kirtland Road | 0.380 | 0.916 | 0.220 | 0.271 | 0.133 | 1.830 | 0.269 | 1.667 | 1.667 | 0 | 0.184 | 6 |
| All scenarios except 2B | All Mill Creek Sites | 0 | 0 | 0.398 | 0.741 | -1.103 | 1.489 | 0.561 | 2.549 | 2.693 | 0 | 0.184 | 6 |
| **Simulation scenarios with upstream dependent curves** | | | | | | | | | | | | | |
| Copper, water, unfiltered, recoverable, µg/L, p01042 | | | | | | | | | | | | | |
| All scenarios except 2B | All sites | -0.875 | 0.792 | 0.147 | 2.729 | – | – | – | – | – | – | – | – |

## Simulating Runoff Treatment

The provision of runoff treatment was evaluated to assess the potential effects of flow reduction, concentration reduction, and hydrograph extension by stormwater control measures, commonly identified as BMPs, on discharges to the receiving streams and on flows, concentrations, and loads of selected constituents in the receiving water downstream from the site of interest. The BMP effluent concentrations and discharge volumes were simulated by using the BMP-treatment module in SELDM (Granato, 2013, 2014). The SELDM BMP module uses the trapezoidal distribution and the rank correlation with the associated highway-runoff variable to provide a stochastic transfer function to approximate the quantity and quality of BMP effluent, given the associated inflow values in a simulation. SELDM uses rank correlation to preserve the structure of inflow and outflow data commonly present in BMP studies. Correlations between the ratio of outflow to inflow volumes and the magnitude of inflows commonly are positive because it would be difficult for BMPs built with commonly used designs to retain or infiltrate a large proportion of flow from a large runoff event. The small positive correlation between highway inflow volumes and the outflow ratios (the ratio of outflow to inflow) reduces the average effectiveness of flow reduction by the BMP. Correlations between the concentration ratio (the ratio of outflow concentration to inflow concentration) and inflow concentrations are negative because BMP-monitoring datasets indicate that BMPs are more effective for substantially reducing large inflow concentrations than small inflow concentrations. The negative correlation between highway inflow concentrations and the outflow ratios increases the average effectiveness of concentration reduction by the BMP. In many studies, BMP outflow concentrations can exceed low inflow concentrations (Granato, 2014; Taylor and others, 2014). To represent this phenomenon, SELDM simulates the effect of the minimum irreducible concentration (MIC), which is the lowest expected BMP effluent concentration (Granato, 2013, 2014). SELDM substitutes the MIC for BMP effluent concentrations that are less than the MIC.

For these analyses, a generic BMP was simulated by using the median of treatment statistics for flow reductions, hydrograph extensions, concentration reductions, and MICs from nine BMP categories with data from the 2012 International BMP Database (Granato, 2014). The BMP categories and associated performance statistics from which the median values were derived for further analysis are shown in table 22. The categories bioretention, composite BMPs, detention basin, biofilter (swale), media filter, retention pond, wetland basin, and wetland channel were selected because flow statistics, concentration statistics, and MIC statistics were available from multiple BMP monitoring sites for these categories (Granato, 2014). The MIC values selected for these simulations were based on the 25th percentile of MIC estimates from available sites for each category. Use of a generic BMP with the median of median performance statistics is warranted for simulating the results of runoff within a watershed with multiple sources because it is unlikely that all the BMPs in the watershed are all of one type, designed for optimum performance, and maintained sufficiently to meet the designed performance standards (Taylor and others, 2014).

The SELDM BMP-Performance module incorporates provisions for the stochastic modeling of three types of highway stormwater treatment: volume reduction, hydrograph extension, and water-quality treatment (Granato 2013, 2014). Volume reduction represent less highway discharge reaching the stream. Hydrograph extension “flattens” the highway discharge hydrograph, potentially resulting in lower peak discharge and EMCs, even though the total highway-runoff load is unchanged. Water-quality treatment potentially results in lower constituent concentrations and loads in the highway discharge.

Analysis of BMP use specific to Oregon was beyond the scope of this study, so a generic BMP was simulated by using the median of treatment statistics for flow reductions, concentration reductions, and MICs from seven BMP categories with data from the 2012 International BMP database (Geosyntec Consultants and Wright Water Engineers, 2016). The reduction in constituent concentration from the generic BMPs applied to each road crossing for TP, TCu, and SSC from highway runoff in SELDM simulations are shown in table 22.

**Table 22.** Stormwater control measure best-management practice performance statistics for flow and concentration treatment used in Stochastic Empirical Loading and Dilution Model.

[Source: Granato, 2014. Total phosphorus (p00665), Phosphorus water, unfiltered, milligrams per liter. Suspended sediment concentration (p80154), Suspended sediment concentration, milligrams per liter. Total copper (p01040), Total copper water, unfiltered, micrograms per liter. The alpha-numeric identifiers starting with "p" are the U.S. Environmental Protection Agency parameter codes. The concentration-reduction and flow-reduction statistics are for the trapezoidal distribution of the ratio of outflow to inflow concentration or flow volume. The Spearman's rho correlation coefficients are calculated by using the ranks of the inflow concentrations or flows and the associated ratios of outflow to inflow concentrations or flows. The MIC estimates for the suspended sediment concentrations (p80154) were developed with total suspended solids (p00530) concentrations, but are considered applicable for estimating the MIC of suspended sediment concentrations because differences in the results of these analytical methods are small once the large grain-size fractions are removed within the BMP. **Abbreviations:** BMP, best management practice; LBMPV, lower bound of the most probable value; MIC, minimum irreducible concentration, NA, not applicable; Rho, Spearman's correlation coefficient; UBMPV, upper bound of the most probable value; —, insufficient data]

| BMP type | Minimum | LBMPV | UBMPV | Maximum | Rho | MIC |
|---|---|---|---|---|---|---|
| Flow Reduction | | | | | | |
| Bioretention | 0 | 0.019 | 0.152 | 0.947 | 0.61 | NA |
| Composite | — | — | — | — | — | NA |
| Detention basin | 0.147 | 0.147 | 0.657 | 1.232 | 0.07 | NA |
| Biofilter (swale) | 0.06 | 0.306 | 0.495 | 1.085 | 0.29 | NA |
| Infiltration basin | — | — | — | — | — | NA |
| Media filter | 0.113 | 0.742 | 0.742 | 1.262 | 0 | NA |
| Retention pond | 0.208 | 0.665 | 0.903 | 1.832 | 0 | NA |
| Wetland basin | 0.136 | 0.934 | 0.934 | 1.233 | 0.21 | NA |
| Wetland channel | 0.116 | 0.548 | 0.548 | 1.849 | 0.27 | NA |
| Median | 0.116 | 0.548 | 0.657 | 1.233 | 0.21 | NA |
| Hydrograph extension | | | | | | |
| Bioretention | — | — | — | — | — | NA |
| Composite | — | — | — | — | — | NA |
| Detention basin | 0 | 0 | 0 | 18 | 0.57 | NA |
| Biofilter (swale) | 0 | 0 | 0 | 3 | 0.45 | NA |
| Infiltration basin | — | — | — | — | — | NA |
| Media filter | 0 | 0 | 0 | 77 | 0.41 | NA |
| Retention pond | 0 | 0 | 0 | 40 | 0.45 | NA |
| Wetland basin | 0 | 0 | 0 | 8 | 0.20 | NA |
| Wetland channel | — | — | — | — | — | NA |
| Median | 0 | 0 | 0 | 18 | 0.45 | NA |
| Total phosphorus (p00665) reduction | | | | | | |
| Bioretention | 0.013 | 0.176 | 0.325 | 2.339 | -0.42 | 0.01 |
| Composite | 0 | 0.126 | 0.17 | 1.562 | -0.571 | 0.005 |
| Detention basin | 0.24 | 0.415 | 0.561 | 1.55 | -0.498 | 0.03 |
| Biofilter (swale) | 0.105 | 0.669 | 0.827 | 3.556 | -0.669 | 0.01 |
| Infiltration basin | 0.002 | 0.002 | 0.031 | 3.649 | -0.292 | 0.002 |
| Manufactured device | 0.286 | 0.445 | 0.664 | 1.533 | -0.212 | 0.003 |
| Media filter | 0.161 | 0.21 | 0.228 | 1.597 | -0.555 | 0.005 |
| Retention pond | 0.053 | 0.199 | 0.38 | 1.653 | -0.606 | 0.006 |
| Wetland basin | 0.056 | 0.512 | 0.88 | 2.158 | -0.517 | 0.008 |
| Wetland channel | 0.171 | 0.226 | 0.623 | 2.203 | -0.401 | 0.007 |
| Median | 0.081 | 0.218 | 0.471 | 1.906 | -0.508 | 0.007 |
| Suspended sediment concentration (p80154) reduction | | | | | | |
| Bioretention | 0 | 0 | 0 | 0.885 | -0.635 | 0.06 |
| Composite | 0 | 0 | 0 | 0.791 | -0.626 | 0.2 |
| Detention basin | 0 | 0 | 0 | 1.158 | -0.631 | 0.89 |
| Biofilter (swale) | 0 | 0 | 0 | 1.545 | -0.569 | 1 |
| Infiltration basin | 0 | 0 | 0 | 0.902 | -0.738 | 1.9 |
| Manufactured device | 0.001 | 0.011 | 0.062 | 1.089 | -0.589 | 0.43 |
| Media filter | 0 | 0 | 0 | 0.652 | -0.604 | 0.43 |
| Retention pond | 0 | 0 | 0 | 0.822 | -0.721 | 0.74 |
| Wetland basin | 0 | 0 | 0 | 1.681 | -0.759 | 0.28 |

**Table 22.** Stormwater control measure best-management practice performance statistics for flow and concentration treatment used in Stochastic Empirical Loading and Dilution Model .—Continued

| BMP type | Minimum | LBMPV | UBMPV | Maximum | Rho | MIC |
|---|---|---|---|---|---|---|
| Wetland channel | 0 | 0 | 0 | 2.21 | -0.446 | 0.2 |
| Median | 0 | 0 | 0 | 0.996 | -0.629 | 0.43 |
| Total copper (p01042) reduction | | | | | | |
| Bioretention | 0.067 | 0.071 | 0.073 | 1.336 | -0.653 | 2.3 |
| Composite | 0.045 | 0.052 | 0.064 | 1.544 | -0.766 | 0.4 |
| Detention Basin | 0.151 | 0.415 | 0.628 | 1.221 | -0.366 | 1.1 |
| Biofilter (swale) | 0.071 | 0.127 | 0.626 | 1.468 | -0.583 | 1.7 |
| Infiltration basin | 0.009 | 0.009 | 0.113 | 1.193 | -0.806 | 3.4 |
| Manufactured device | 0.227 | 0.435 | 0.739 | 1.494 | -0.489 | 0.6 |
| Media filter | 0.112 | 0.245 | 0.43 | 1.36 | -0.357 | 0.28 |
| Retention pond | 0.042 | 0.2 | 0.219 | 1.421 | -0.642 | 0.48 |
| Wetland basin | 0.123 | 0.305 | 0.323 | 1.333 | -0.667 | 0.26 |
| Wetland channel | 0.156 | 0.607 | 0.67 | 2.113 | -0.775 | 0.43 |
| Median | 0.092 | 0.223 | 0.377 | 1.391 | -0.648 | 0.54 |

# Example Runoff-Quality Simulations

Five different simulation scenarios were performed (table 23). The first two simulations (scenarios 1 and 2) were designed to demonstrate potential uses of SELDM for working within nested watersheds. The remaining three simulations (scenarios 3–5) were designed to investigate how changes made to particular parameters, such as highway design, road width, and impervious area, will affect concurrent downstream stormflow conditions. These three simulations serve as a type of sensitivity analysis for each parameter investigated.

**Table 23.** List of SELDM simulation scenarios and inputs developed for Bear and Mill Creek watersheds, Oregon.

[Table 23 is an Excel® file available for download at https://doi.org/10.3133/sir20195053]

Scenarios 3–5 were run using the Mill Creek at Turner station. These scenarios were not run at all sites because these are meant to serve as a demonstration of how SELDM can be used for decision-making, not to thoroughly investigate the effect of these parameters at multiple locations within a watershed. The Mill Creek at Turner station was selected because many of the input parameters at that site (including precipitation values, road width, and drainage area) are at or near the median of the seven Mill Creek sites, so the results of simulations at that site are more transferable to other parts of the watershed than would be a site with values that deviate more from the medians.

SELDM can be used to assess the risk of exceeding any proposed discharge-concentration criterion with and without use of BMPs. Numeric acute water-quality criteria, which are commonly calculated by using base-flow concentration statistics, were selected for each of the three constituents of interest. The acute criteria are officially known as the Criteria Maximum Concentration (CMC), which is “the highest concentration of a pollutant to which aquatic life can be exposed for a short period of time without deleterious effects” (U.S. Environmental Protection Agency, 1994; 2000; 2018, p. 52,218). That “short period of time” commonly is interpreted as 1 hour, but because stormflow concentrations are measured as EMCs, the CMC is applied to individual runoff events (which may be of varying duration) for discussion in this report (see section, “Limitations of the Analyses”). These criteria are used herein only as values that can be used in the discussion of risk-based decision making. Selection of these criteria for discussion does not indicate that they are protective of the designated uses or otherwise suitable for use in Oregon. Furthermore, Granato and Jones (2015) determined that water-quality criteria may not be applicable to stormwater quality even in the absence of anthropogenic inputs. Data collected for promulgating such criteria commonly are more representative of base-flow (low streamflow) water-quality than stormflow quality, and concentrations of many constituents are elevated by natural runoff and transport processes that occur during periods of stormflow. Therefore, these criteria, many of which were developed for dilution of municipal wastewater into receiving streams during low streamflow periods, may not be achievable if used as a runoff-discharge criteria.

The criteria selected for discussion in this report were based on available information for each constituent. For TP, a criterion-concentration of 0.1 mg/L was selected for discussion based on previous USEPA criteria to control algal growth for streams or flowing waters not discharging into lakes or reservoirs (U.S. Environmental Protection Agency, 1986). The same TP criterion was set for saltwater in Oregon (Oregon Department of Environmental Quality, 2018c), although no statewide freshwater criteria have been set as of 2018. This TP criterion is also consistent with the Willamette Valley water-quality benchmarks referenced by Oregon Department of Environmental Quality (2009), which sets a concentration of 0.110 mg/L of TP as “poor.”

For TCu, a criterion-concentration of 0.3 microgram per liter (µg/L) was selected for discussion as a limit that is likely to be near the lower bounds of analysis based on use of 2018 guidelines for Oregon (McConaghie and Matzke, 2016; Oregon Department of Environmental Quality, 2016). This TCu limit also is stringent because the current methodology used in Oregon is based on the Biotic Ligand Model (BLM), which is used to estimate a criterion for dissolved copper (DCu) rather than TCu. Risley and Granato (2014) did an analysis of stochastic variations in the contemporaneous water hardness-based TCu criteria. Based on average hardness values for the ecoregions of interest, the criterion concentrations for TCu were 4.65 µg/L in the Willamette Valley Ecoregion and 7.58 µg/L in the Klamath Mountains Ecoregion. Based on dilution of hardness with increasing stormflow, hardness-based TCu criteria ranged from 1.01 to 19.2 µg/L in the Willamette Valley Ecoregion and from 3.83 to 27.3 µg/L in the Klamath Mountains Ecoregion with median values of 4.38 and 7.25 µg/L, respectively (Risley and Granato, 2014). The 0.3 µg/L value was selected for discussion herein because the BLM estimates are more rigorous than previously used aquatic criteria, and the BLM estimates and dilution of the major ions that comprise the hardness values with increasing stormflow also tend to depress BLM criteria for metals. However, if water-quality criteria are applied to stormwater discharges, then the ODEQ-industrial discharge benchmark-criterion of 20 µg/L for TCu (McConaghie and Matzke, 2016) may be more suitable for runoff than an instream criterion because of the limitations of BMP technologies (Taylor and others, 2014; Granato and Jones, 2015).

In the absence of an identifiable statewide SSC criterion for Oregon in 2018, a criterion value of 80 mg/L, which is the criterion value used in neighboring States (Idaho Department of Environmental Quality, 2003), was selected for use in the risk-based discussions herein.

Water-quality criteria designed to protect the ecology of receiving streams commonly are composed of two components: the criterion concentration and the allowable-exceedance frequency. Water-quality criteria commonly are defined with an allowable exceedance frequency in recognition of the large variability in concentrations and flows that may occur over a long period of time (U.S. Environmental Protection Agency, 1994). The U.S. Environmental Protection Agency (1994) selected a once-in-three year exceedance frequency as a protective measure to provide for ecological recovery from periods of severe stress.

Because this study uses event-based simulations, this exceedance frequency is based on the number of storms. Therefore, the risks discussed are based on the number of events, not the amount of time (Granato, 2013). For any one event, there is an exceedance probability that the constituent concentration downstream from the road crossing will be at or above a specific water-quality criterion. For example, hypothetical results might indicate that there is a 2.0 percent chance of exceedance. In such an instance, the probability of any given storm event equaling or exceeding the criterion of interest is 1 in 50 (1/0.02).

In the Bear Creek watershed, there are about 36 storm events per year on average (table 24), which equates to about 108 events over a 3-year period. Therefore, to meet the EPA criteria of having only one constituent concentration exceedance every 3 years, the allowable rate of exceedance for individual storms is about 0.94 percent (1/108). In the Mill Creek watershed, there are about 50 storm events per year on average, which results in a 3-year risk of about 0.66 percent for each exceedance (table 24). It should be noted that highway runoff approximates the duration of time in which a runoff-producing precipitation event occurs. For a given year, this represents on average about 4 percent of the time (that is, there will be no highway runoff about 96 percent of the time during a given year). Therefore, the actual risk of exceedance for runoff events is smaller than the associated time-based risk. The event-based risks for the watershed will be plotted as target exceedance probability (0.0094 for Bear Creek and 0.0066 for Mill Creek) in subsequent figures.

**Table 24.** Allowable exceedance probabilities for stations in the Bear and Mill Creek watersheds, Oregon.

[**Percentage allowable:** The maximum percentage of storms in which on mean one exceedance will occur once every 3 years]

| Site | Number of storms | Number of years | Storms per year | Percentage allowable |
|---|---|---|---|---|
| | | Bear Creek watershed | | |
| Emigrant Creek at Highway 66 | 1,341 | 39 | 34.4 | 0.97 |
| Emigrant Creek at Ashland | 1,397 | 39 | 35.8 | 0.93 |
| Hamilton Creek | 1,394 | 39 | 35.7 | 0.93 |
| Bear Creek at Talent | 1,405 | 39 | 36.0 | 0.93 |
| Bear Creek at Phoenix | 1,377 | 39 | 35.3 | 0.94 |
| Bear Creek at Interstate-5 | 1,401 | 39 | 35.9 | 0.93 |
| Bear Creek at Kirtland Road | 1,410 | 39 | 36.2 | 0.92 |
| Mean | 1,389 | 39 | 35.6 | 0.94 |
| | | Mill Creek watershed | | |
| Mill Creek at Boedigheimer Road | 1,974 | 39 | 50.6 | 0.66 |
| Mill Creek at Stayton | 1,988 | 39 | 51.0 | 0.65 |
| Mill Creek at Aumsville | 1,958 | 39 | 50.2 | 0.66 |
| Mill Creek at Mill Creek Road | 1,958 | 39 | 50.2 | 0.66 |
| Mill Creek at Turner | 1,974 | 39 | 50.6 | 0.66 |
| Mill Creek at Interstate-5 | 1,944 | 39 | 49.8 | 0.67 |
| Mill Creek at Mission Street | 1,944 | 39 | 49.8 | 0.67 |
| Mean | 1,963 | 39 | 50.3 | 0.66 |

## Simulation Scenario 1—Natural Conditions

Simulation Scenario 1 was designed to represent a situation in which one or more road crossings representing the actual road configuration and drainage areas are added to what is an otherwise undeveloped watershed (called ‘natural conditions’ in the simulation scenario label). As a general rule, the more drainage area that is upstream from a stream/road crossing, the less effect that road crossing will have on the overall constituent EMCs of a stream. The assumption is that most watersheds gain streamflow with additional drainage area (this may not be the case if there are reaches with substantial streamflow loss); that runoff from roads tends to have higher constituent-concentrations than what is carried in the stream; and that an additional set amount of runoff-constituent input from a proposed road crossing will represent a smaller proportion of the overall flow as the drainage area increases.

Figure 11 shows a schematic of Simulation Scenario 1. The upstream stormflows and concentrations were derived assuming the area upstream from the highway is undeveloped. The highway represents the real-world conditions at that highway. The downstream concentrations and stormflows represent the stream conditions just downstream from the highway. If a BMP is implemented, it would influence the highway concentrations and (or) stormflows.

### Runoff-Quality Risk Analysis

SELDM can be used to assess the risk of exceeding the specified streamflow concentration criteria with and without the use of BMPs. Figure 12 is an example of a cumulative distribution function plot of SELDM results. In this instance, the results are from the Emigrant Creek at Highway 66 site in the Bear Creek watershed, which was arbitrarily chosen to be used often as an example for this report.

To evaluate the likelihood of a watershed exceeding the target exceedance probability, a dashed vertical line is displayed in figure 12 and many of the similar subsequent figures. This vertical line represents the target exceedance probability of 0.94 percent for sites in the Bear Creek watershed and 0.66 percent for sites in the Mill Creek watershed (average values for each watershed, table 24), which is the highest frequency of storms that would meet the criteria of a return interval of one such storm every 3 years. In figure 12, the horizontal line represents the constituent criterion of 0.1 mg/L of TP. By finding the intersection of the vertical line (the exceedance criterion) with the dots representing concentration of TP, the resulting value along the x-axis represents the percentage chance of any given storm simulated by SELDM resulting in a EMC of TP equal to or greater than the criteria set. The percentage change is represented as probability, or percentage divided by 100. If the vertical line plots to the right of the intersection of the EMC data and the horizontal line representing the constituent concentration criterion, then the estimated frequency is lower than a 3-year return interval, and the model results indicate that the hypothetical water-quality criterion will be achieved.

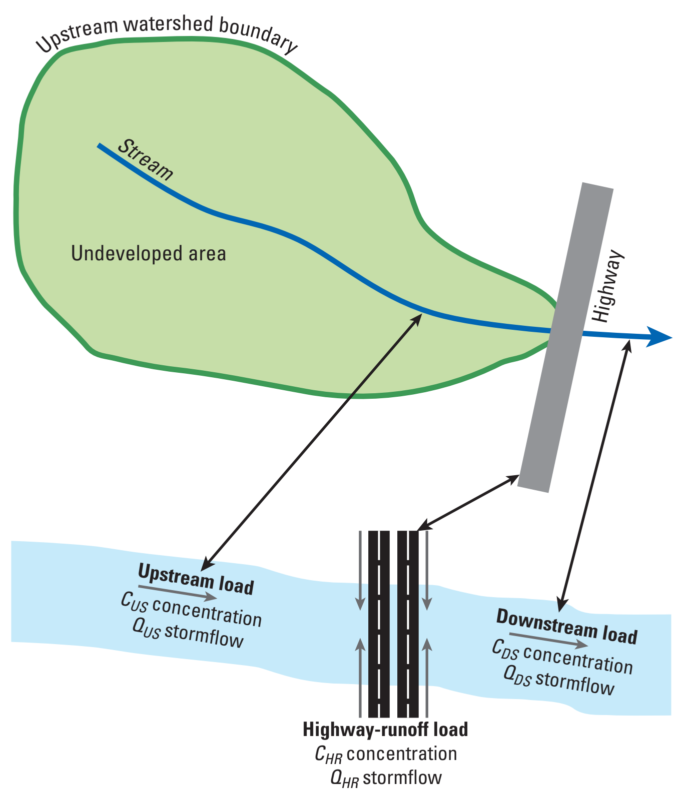



**Figure 11.** Schematic of SELDM Simulation Scenario 1—Natural Conditions. (CDS, concentration of downstream load; CHR, concentration of highway-runoff load; CUS, concentration of upstream load; QDS, stormflow downstream load; QHR, stormflow of highway-runoff load; QUS, stormflow of upstream load)

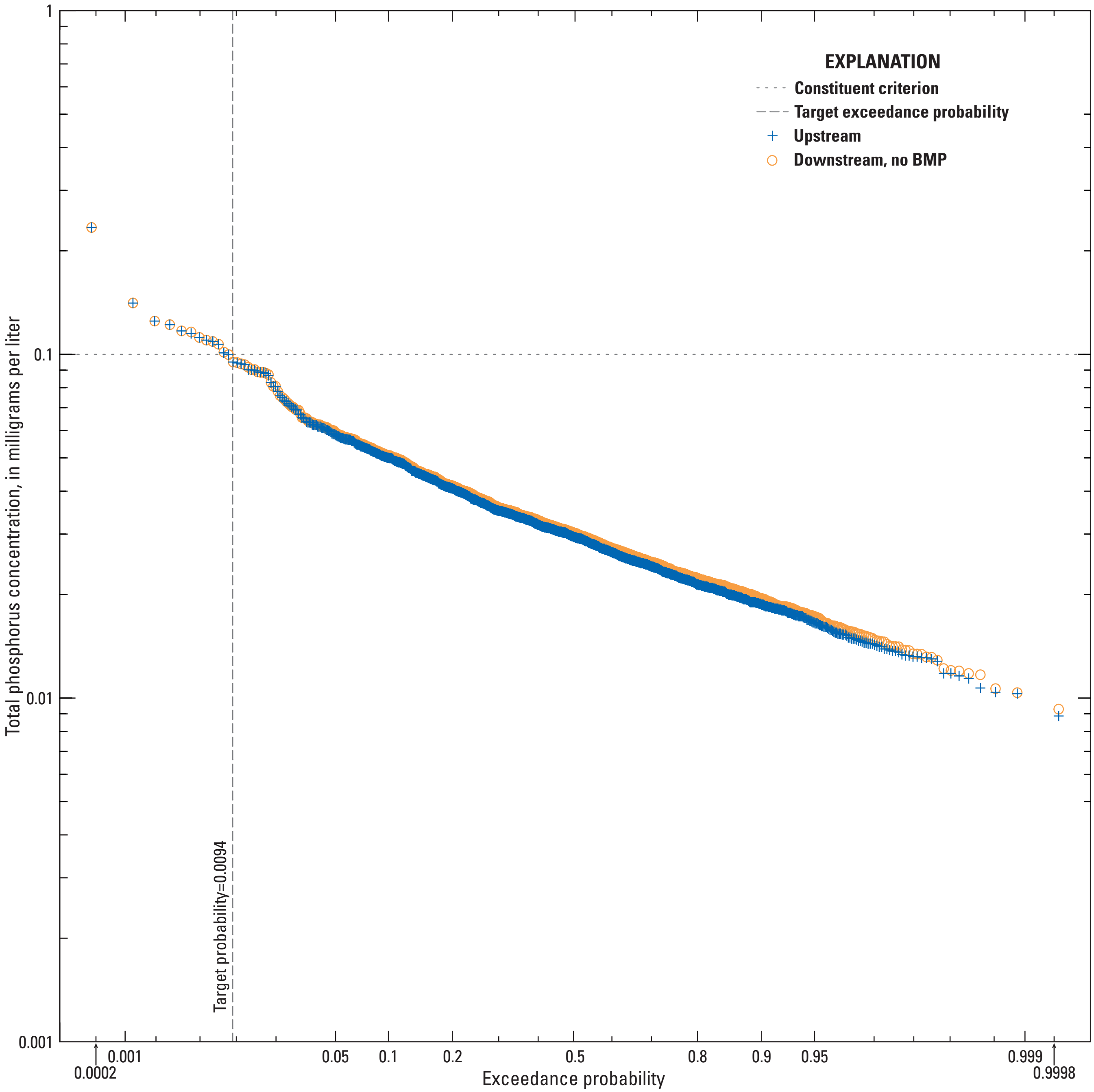



**Figure 12.** Exceedance probabilities of total phosphorous upstream and downstream from the road crossing under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, Emigrant Creek at Highway 66 site, Bear Creek, Oregon.

The scenario results indicate the risk of any given storm resulting in a TP EMC exceedance of 0.1 mg/L downstream from the road crossing is 0.82 percent (fig. 12), which is slightly less than the once-in-three target probability of 0.94 percent. At the same site, but upstream from the point where the highway runoff enters the stream, the probability of a TP EMC in exceedance of the same criteria is approximately the same as downstream from the road crossing (fig. 12). These results indicate that the addition of a road crossing similar to the existing road infrastructure at the Emigrant Creek at Highway 66 crossing would not result in a substantial increase in storm events that exceed the TP concentration criterion of 0.1 mg/L.

Evaluation of the seven sites in the Bear Creek watershed, indicates the risk of exceedance at any of the sites ranges from about 0.6 to 1.5 percent (fig. 13). In this scenario, results suggest the road crossing could be added to the Kirtland Road, Interstate-5 (I-5), Hamilton Creek, or Emigrant Creek at Highway 66 stream sites without a BMP and still meet water-quality targets of concurrent downstream stormflow. A road crossing at any of the other sites (Emigrant Creek at Ashland, and Bear Creek at Talent, Phoenix, and I-5) would result in more downstream exceedances than prescribed, although the upstream frequency of exceedance at each of these sites would also need to be calculated to determine if the water-quality target would not be met without a road crossing.

Downstream road crossings in the Mill Creek watershed also indicate low probabilities of exceeding 0.1 mg/L of TP under Simulation Scenario 1 (fig. 14) and a larger range between the various sites. The probability of any given storm exceeding a TP EMC of 0.1 mg/L ranges from about 0.1 to 2.9 percent, with the sites farthest upstream in the watershed having the highest probability of exceedance. These results indicate that the probability of exceeding the TP threshold of 0.1 mg/L are low for conditions when the watershed upstream from the road crossing is undeveloped. To meet the target of having only one TP EMC exceedance every 3 years in the Mill Creek watershed, the risk of exceedance needs to be approximately 0.66 percent (table 24). In this scenario, the road crossing could be added to any of the five most-downstream sites without a BMP and still meet water-quality targets of concurrent downstream stormflow because adding a road crossing has little effect on the frequency of TP exceedances, similar to the results for Emigrant Creek (fig. 12). Placing the road crossing at either the Stayton or Boedigheimer Road site would result in more than one exceedance every 3 years without a BMP. At these two most upstream sites in the watershed, TP EMCs upstream from the road crossings already exceed the selected criteria more frequently than once every 3 years (results not shown). Placement of a road crossing at one of these two sites would not result in a substantially higher frequency of TP EMC exceedances. The rate of exceedance resulting from the addition of a road crossing increased by less than 0.1 percent at both sites (values not shown).

Simulation results for TCu at Emigrant Creek at Highway 66 indicate that upstream EMCs are more likely to be above the constituent criteria than the frequencies predicted from the modeled TP values (fig. 15). In addition, although TCu EMCs are similar upstream and downstream from the road crossing at higher concentrations, the two populations diverge at high levels of exceedance probability (at lower concentrations). Upstream and downstream EMCs plot above the constituent criteria of 0.3 μg/L for about 55 and 66 percent of the storm events, respectively.

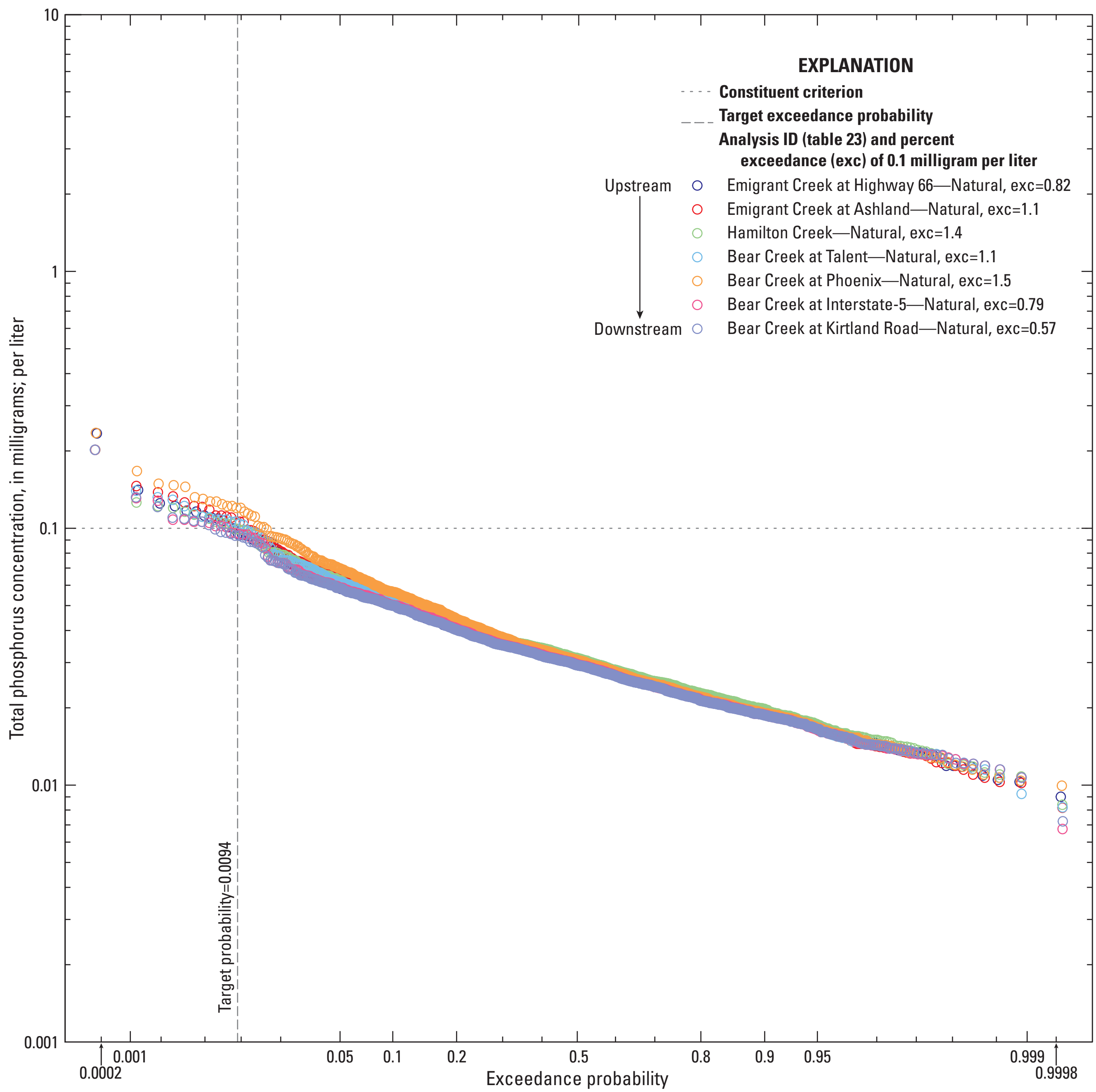



**Figure 13.** Downstream exceedance probabilities of total phosphorous under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, at Bear Creek sites, Oregon.

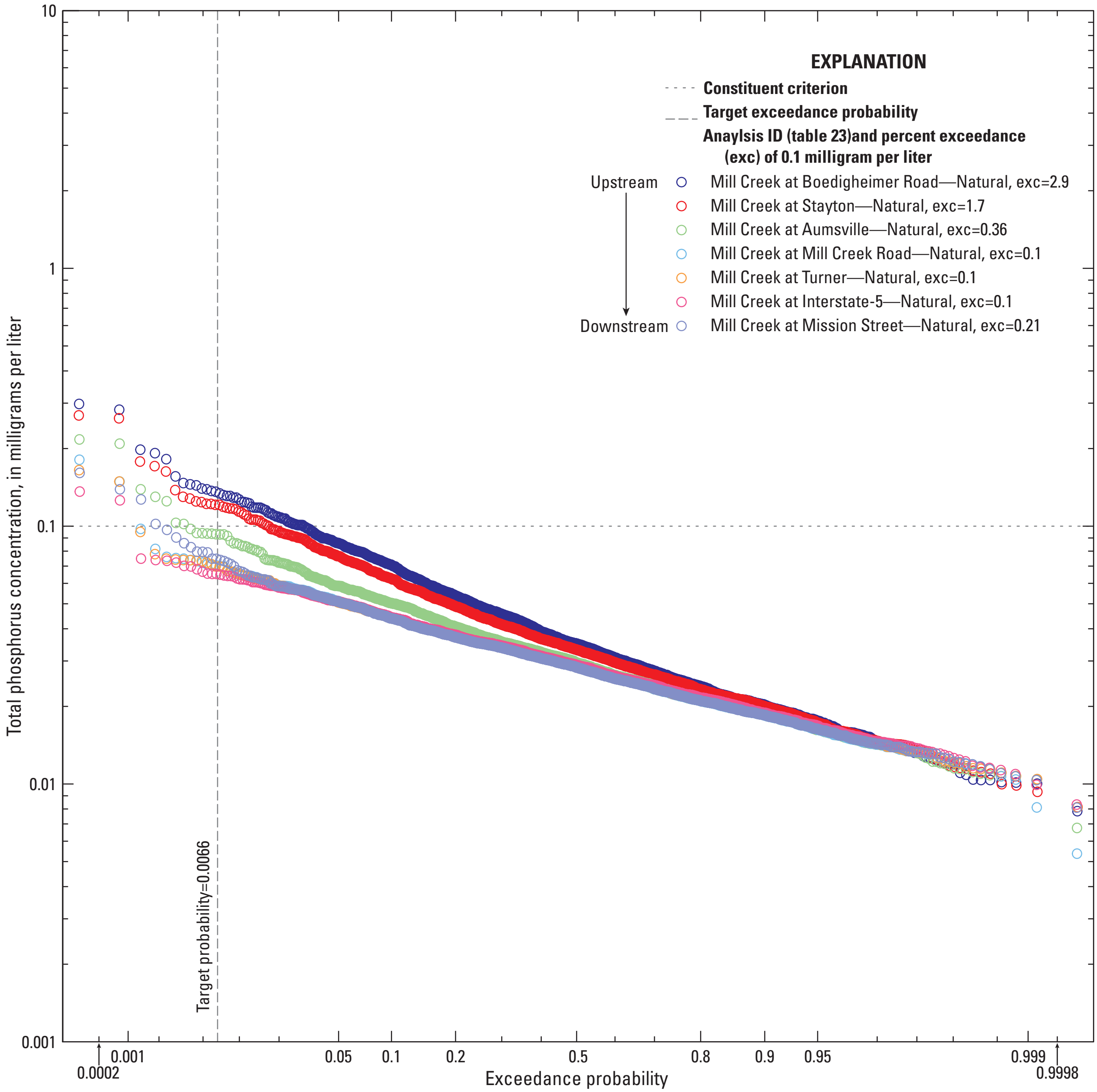



**Figure 14.** Downstream exceedance probabilities of total phosphorous under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, at Mill Creek sites, Oregon.

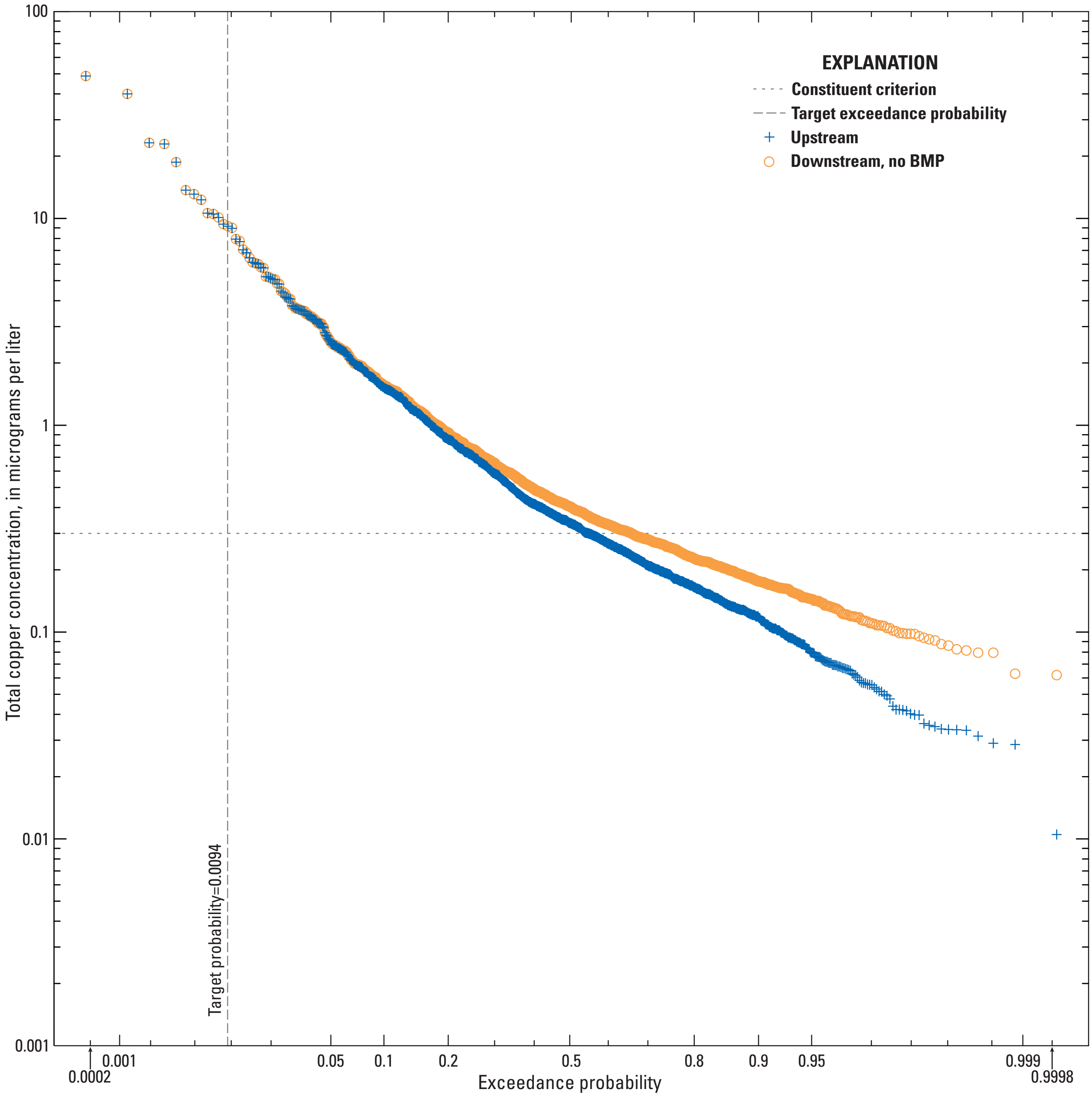



**Figure 15.** Exceedance probabilities of total copper upstream and downstream from the road crossing under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, at the Emigrant Creek at Highway 66 site, Bear Creek, Oregon.

The probability of downstream EMCs exceeding the 0.3-μg/L threshold set for TCu is relatively higher than TP in Bear Creek sites (fig. 16) and in Mill Creek sites (fig. 17). The site with the highest likelihood of downstream TCu exceedance in the Bear Creek watershed is Hamilton Creek (92 percent). This is a result of the high dilution factor relative to the other sites in the watershed. Hamilton Creek has an upstream drainage area of only 0.7 $mi^2$ (table 23), so the runoff from the roadway typically constitutes a higher percentage of flow downstream from the crossing than at other sites. Conversely, the Kirtland Road site has the highest upstream drainage area, and consequently the lowest risk of exceedance (52 percent).

The TCu results are similar in the Mill Creek watershed (fig. 17). The site with the smallest drainage area (Boedigheimer Road) has the highest probability of exceedance (55 percent), whereas the site with the largest drainage area (Mission Street) has the lowest probability of exceedance (19 percent). The I-5 crossing is an outlier here, as it has a larger probability of exceedance than the Turner or Mill Creek Road crossings, despite having a larger drainage area than both sites. This is due to the input from the highway itself, because the I-5 highway drainage area is larger than the other roadway areas (6.93 acres, table 5) and consequently has a higher mean event highway load. The modeled mean event highway load from the I-5 site is 0.0241 pounds (10.9 grams) of TCu, whereas the modeled mean event loads for the Turner and Mill Creek Road sites are 0.00318 pounds (1.44 grams) and 0.00237 pounds (1.08 grams), respectively.

The difference between upstream (no road crossing present) and downstream (road crossing present) EMC distributions at Emigrant Creek at Highway 66 is much greater for SSC than for either TP or TCu (fig. 18). With no road crossing present, model results indicate that upstream values would be below the SSC criterion in greater than 99.9 percent of events. Model results indicate the addition of a road crossing would result in markedly higher downstream EMCs, and a greater chance of exceeding the SSC criterion (1.8 percent). These results indicate that individual road crossings can be substantial sources of sediment. Similar differences between upstream and downstream EMCs are seen at other sites in both the Bear and Mill Creek watersheds (simulations not shown).

For the Bear Creek watershed, the Phoenix site indicates the highest probability of downstream SSC threshold exceedance (fig. 19). This occurs in part because the Phoenix site has the largest highway catchment drainage area of any site in the Bear Creek watershed (table 4), and because the Phoenix site has the largest transport curve slope for relatively high streamflows (table 21). Therefore, the undeveloped background EMCs are higher and the highway loads are higher than at other sites. All other sites have exceedance probabilities of 1.8–2.6 percent. With the criterion of 80 mg/L of SSC, relatively large background concentrations (for example, fig. 18) coupled with markedly high highway inputs indicate that achieving the target exceedance probabilities may not be possible without BMP implementation. The Mill Creek sites have downstream exceedance probabilities that range from near 0 to 1.5 percent, with the smaller, upstream sites tending to have the largest risk of SSC exceedance (fig. 20). The road crossing simulation results indicate that downstream water quality meets the example criteria at any of the five most-downstream locations downstream from the road crossing without the use of a BMP.

## Runoff Treatment Analyses

At a specific location for a given simulation scenario, the effects of BMP implementation on downstream EMCs can be evaluated. For example, at the Mill Creek at Boedigheimer Road site, the TCu EMC of the average concurrent downstream stormflow is estimated as 0.728 mg/L without BMP implementation, and 0.709 mg/L with BMP implementation (fig. 21). The average instream effectiveness of BMP implementation can be seen by the magnitude of departure from the 1:1 line in figure 21. Points that are to the left of the line represent a more substantial reduction in concurrent downstream stormflow TCu EMCs, whereas points directly on the line represent no reduction in EMC. At higher instream concentrations of TCu, which in this simulation scenario are typically associated with higher streamflow and highway-runoff volumes, the simulated BMP seems to be ineffective because the highway contributions are small in comparison to the upstream contributions; even a highly effective BMP would have limited effect for such events when the highway contributions are a small fraction of downstream flows. Conversely, TCu EMCs representative of lower flow conditions indicate a wide range of effectiveness.

As configured, model results estimate that the BMP reduces the mean highway runoff TCu EMC by about one-half at the Mill Creek at Boedigheimer Road site (fig. 22). With the BMP in place, TCu EMCs of concurrent downstream stormflows are close to EMCs of concurrent upstream stormflows. For the Boedigheimer Road site, implementation of a BMP results in the probability of any given event exceeding the water-quality criteria dropping from 55 (fig. 15) to 52 percent (fig. 23). Results indicate that the implementation of a BMP at other locations within the Mill Creek watershed would have varying degrees of efficacy. For example, at the Mill Creek at I-5 location, which has the largest road catchment of any of the seven crossing, model results indicate the probability of exceeding the TCu water-quality criterion drops from 27 (fig. 17) to 19 percent (fig. 23). Conversely, at the Mission Street crossing, which has the smallest road catchment, results indicate the addition of a BMP produces no improvement in the rate of TCu water-quality criteria exceedances downstream (19 percent under each scenario; figs. 17 and 23).

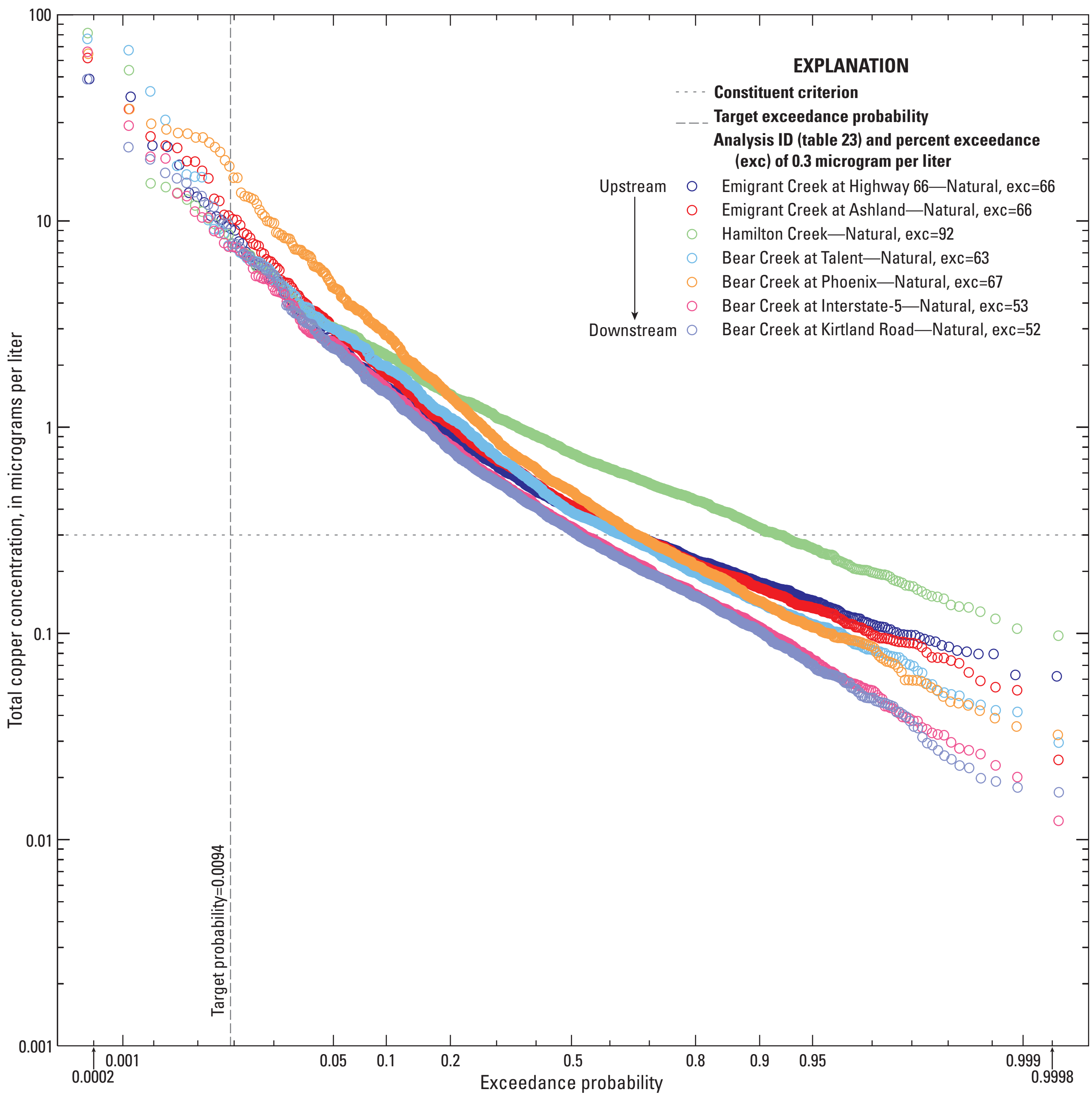



**Figure 16.** Downstream exceedance probabilities of total copper under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented at Bear Creek sites, Oregon.

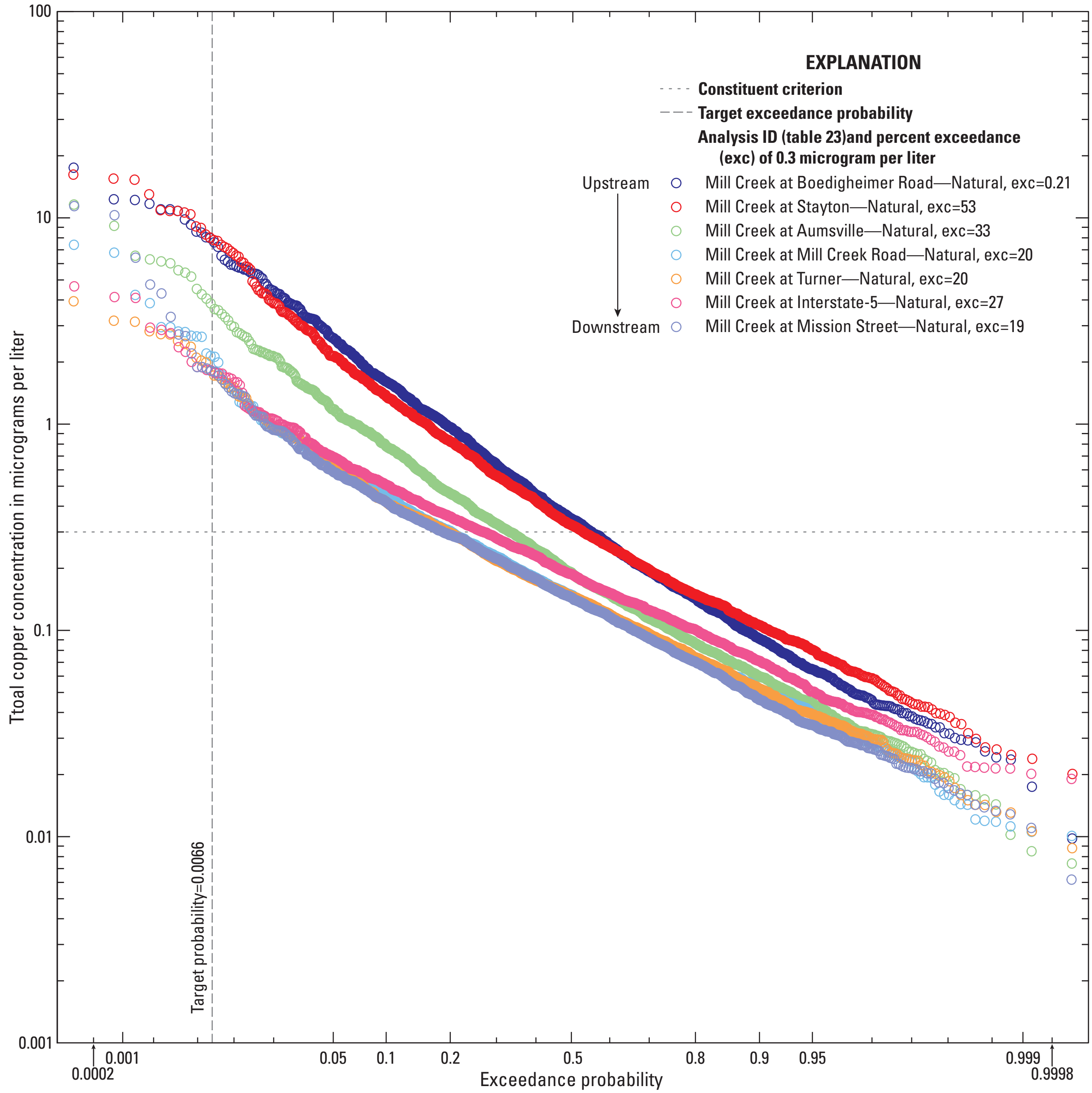



**Figure 17.** Downstream exceedance probabilities of total copper under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, at Mill Creek sites, Oregon.

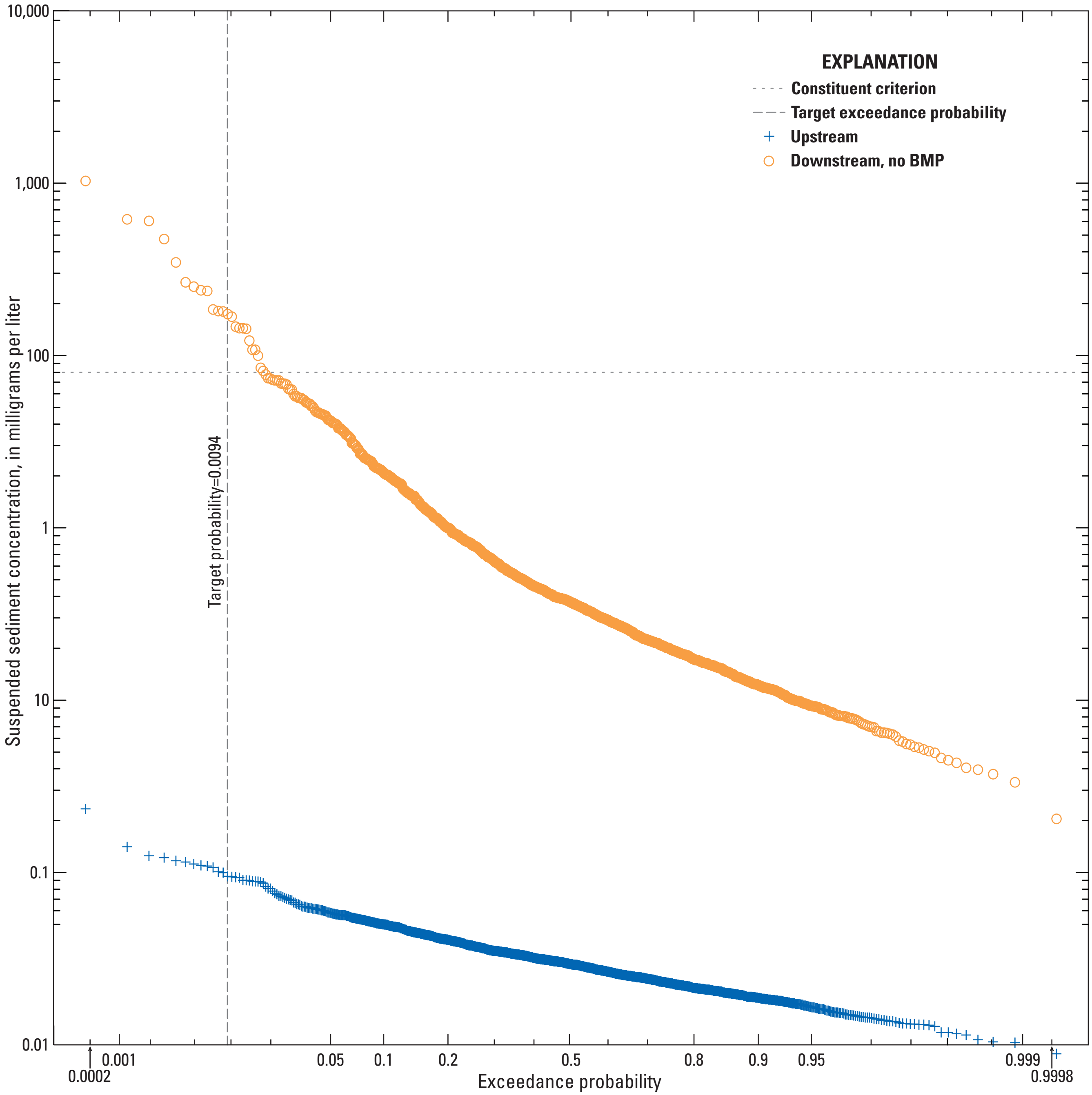



**Figure 18.** Exceedance probabilities of suspended-sediment concentration upstream and downstream from the road crossing under Simulation Scenario 1—Natural Conditions with no best management practice (BMP) implemented, Emigrant Creek at Highway 66 site, Bear Creek, Oregon.

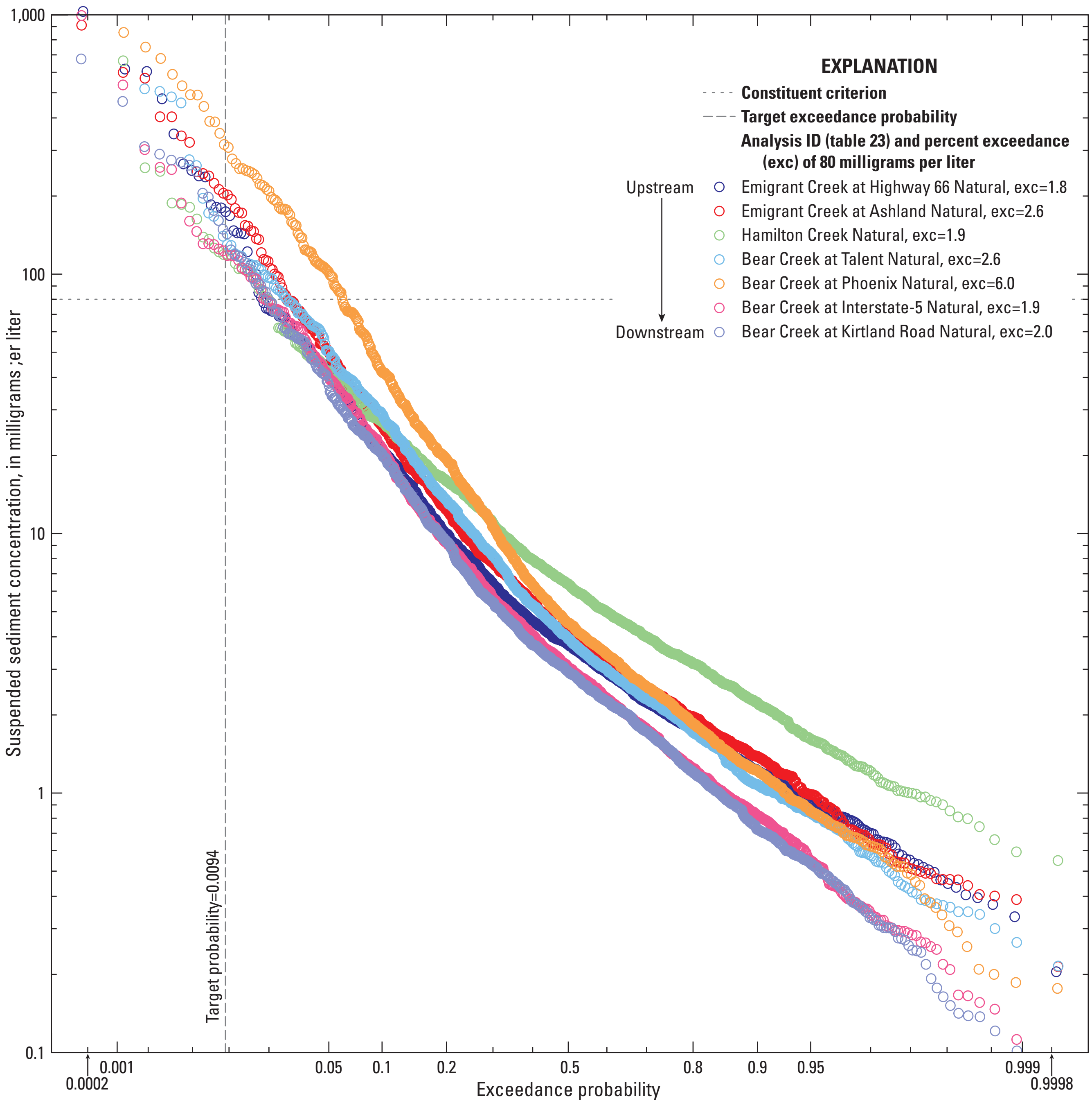



**Figure 19.** Downstream exceedance probabilities of suspended sediment concentration under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, at Bear Creek sites, Oregon.

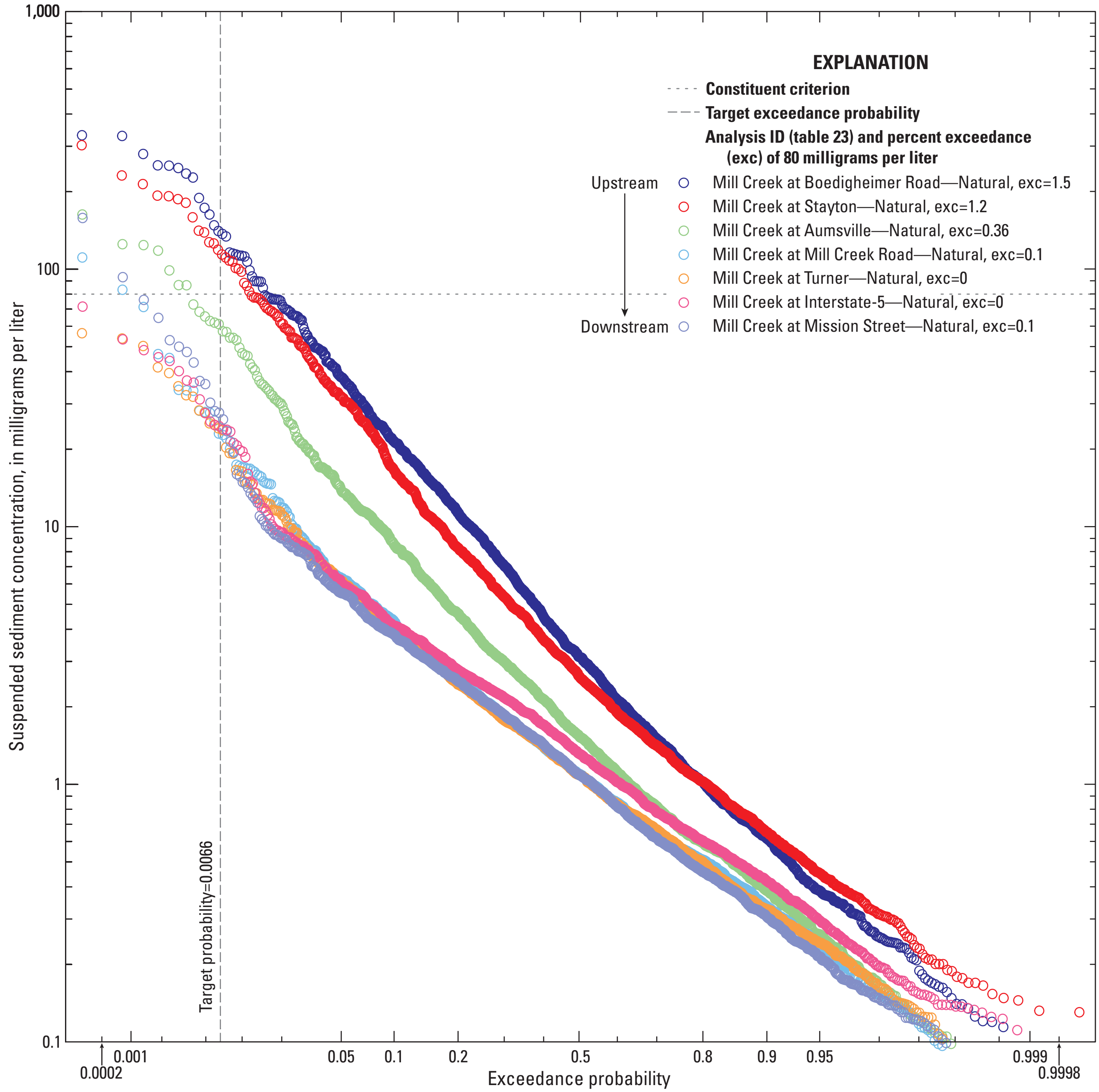



**Figure 20.** Downstream exceedance probabilities of suspended sediment concentration under Simulation Scenario 1—Natural Conditions, with no best management practice (BMP) implemented, at Mill Creek sites, Oregon.

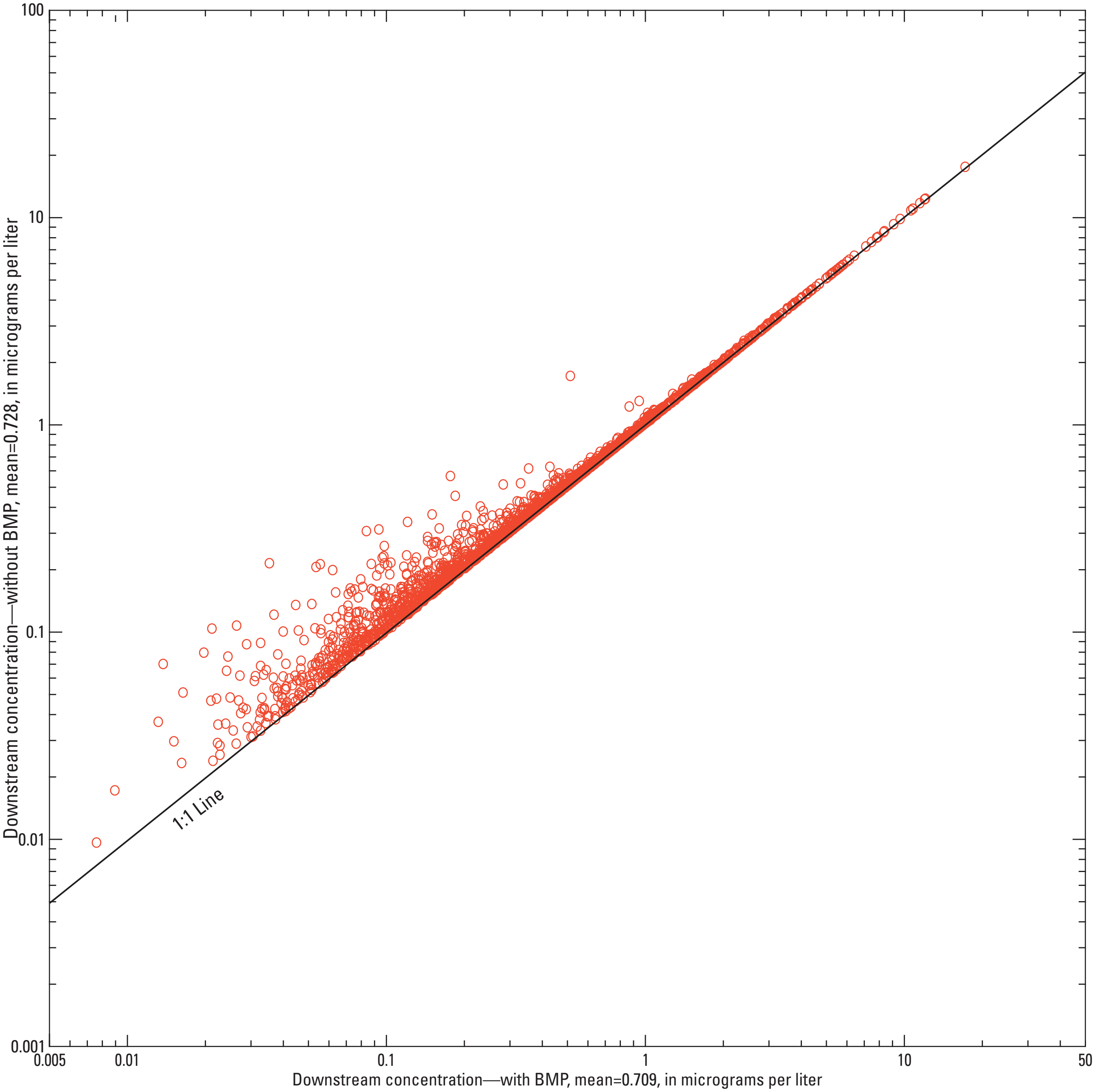



**Figure 21.** Downstream concentrations of total copper with and without best management practice implementation for Simulation Scenario 1—Natural Conditions, at Boedigheimer Road crossing of Mill Creek, Oregon.

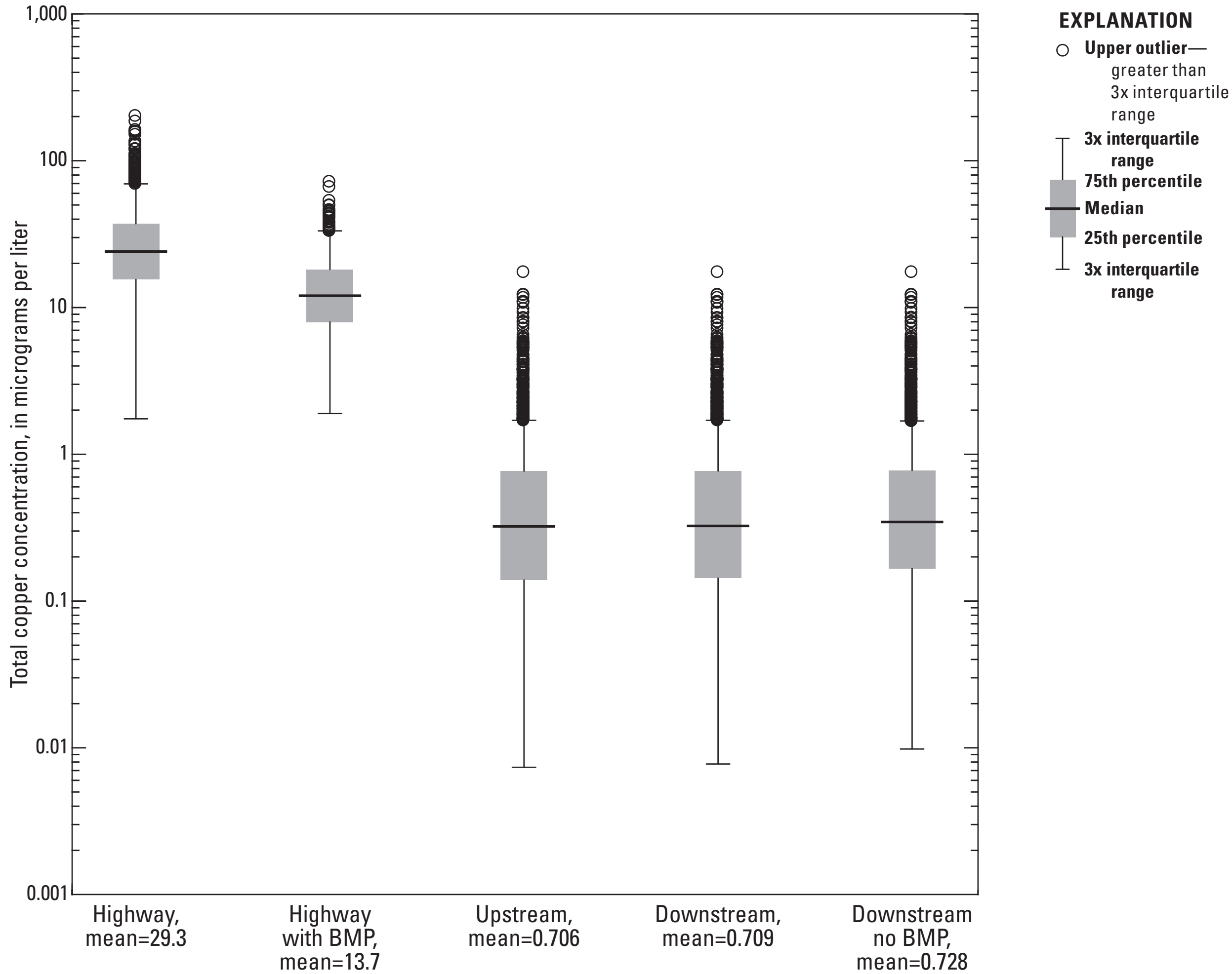



**Figure 22.** Boxplots of highway, upstream, and downstream concentrations of total copper under Simulation Scenario 1—Natural Conditions with and without best management practice (BMP) implementation, at Boedigheimer Road crossing of Mill Creek, Oregon. Mean values in micrograms per liter.

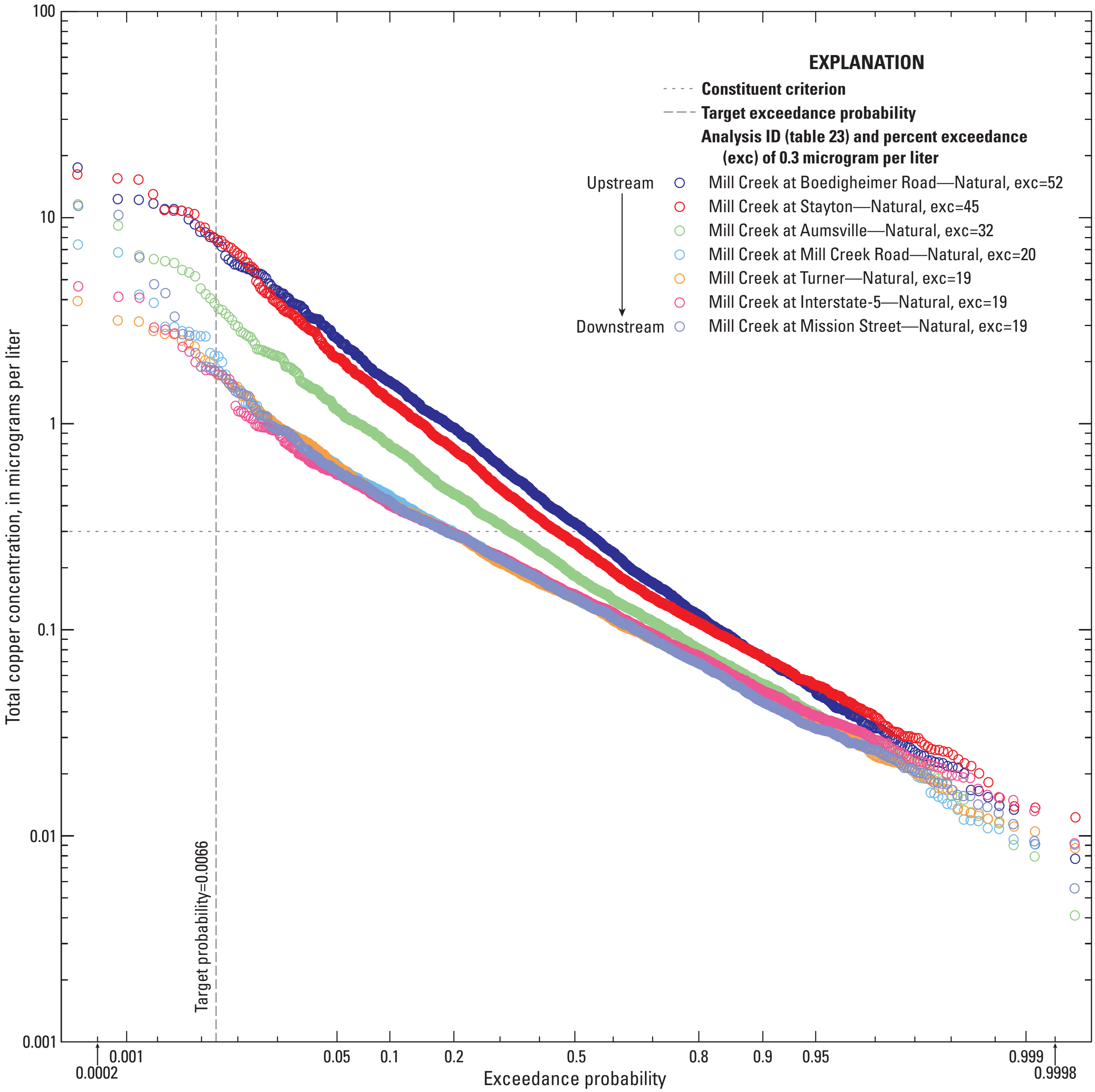



**Figure 23.** Downstream exceedance probabilities of total copper concentration under Simulation Scenario 1—Natural Conditions, with best management practice (BMP) implemented, at Mill Creek sites, Oregon.

Model results indicate the implementation of a BMP in Mill Creek would have less substantial effects on TP EMCs (fig. 24) compared to TCu. There are fewer exceedances of the TP water-quality criterion than the TCu criterion with no BMP present. Results indicate that TP exceedances only occur during high flow events, when the highway runoff represents a relatively small proportion of the downstream loads constituent. As a result, construction and maintenance of a BMP at any of the Mill Creek sites does not substantially reduce the probability of exceedance. The effects of a BMP on SSC were similar to the effects on TP (fig. 25), as no substantial decreases in EMCs were noted.

In the Bear Creek watershed, model results indicate the implementation of a BMP would result in fewer downstream water-quality exceedances of TCu from the Hamilton Creek crossing, reducing the probability of exceedance from 92 (fig.16) to 77 percent (fig. 26). This is a result of Hamilton Creek having the smallest ratio of upstream drainage area to highway drainage area (table 4). The crossing with the second-smallest ratio, Emigrant Creek at Highway 66, also indicates an appreciable decrease in the probability of exceedances (from 66 to 56 percent). The other crossings with higher ratios of upstream drainage area to highway catchment areas indicated relatively smaller decreases (between 0 and 2 percent).

Model results indicate the implementation of a BMP in the Bear Creek watershed would not affect the probability of TP exceedance downstream from most road crossings (fig. 27), with the exception of Hamilton Creek (1.4–0.86 percent; figs. 13 and 27), in which case it would result in the crossing meeting the water-quality criterion of one exceedance every 3 years (exceedance probability of 0.93 percent based on table 24). The effect of a BMP on SSC water-quality criterion exceedances in Bear Creek was similar to TP (fig. 28), with only the Hamilton Creek site indicating detectable improvement.

## Runoff-Quality Annual Load Analyses

For each scenario, 39 years of data were simulated to estimate annual highway loading of TP, TCu, and SS. In general, the annual loading of SS is much higher than TP or TCu. For example, without the implementation of a BMP at the Emigrant Creek at Highway 66 site, model results estimate the median annual highway loads of TP, TCu and SS are 4.27, 0.324 and 2,180 pounds per year (lb/yr), respectively (fig. 29, table 25). In this example, the BMP reduces the annual load of SS by 88 percent of the median annual value expected without BMP implementation. In contrast, BMP implementation at this site reduces the median annual load of TCu and TP by 67 and 53 percent, respectively.

Similar reductions in mean annual load were observed in other sites within the Bear Creek and Mill Creek watersheds (table 25). This is to be expected, as the statistics for the ratio of the outflow to inflow concentration is the same for all sites (same generic BMP implementation). Consequently, the only variability results from the stochastically generated numbers in the Monte Carlo simulations for the different scenarios.

As expected, given the configuration of this simulation scenario (consistent constituent highway discharge distribution regardless of location), annual highway loading is largely a function of highway catchment size. Sites with the largest highway catchment area such as Bear Creek at Phoenix, Emigrant Creek at Highway 66, and the Mill Creek sites at I-5 and at Stayton have the largest annual load production relative to other sites within the Bear and Mill Creek watersheds, respectively.

## Simulation Scenario Overview

Simulation Scenario 1 can be used to evaluate the construction of a new road crossing in an otherwise undeveloped watershed, and to evaluate different locations for that road crossing. Results indicate that strategic placement of such a road crossing could be used to avoid exceeding the example water-quality criteria of TP and SSC, but that no location choice will result in meeting the example TCu water-quality criterion, because the TCu EMCs of concurrent upstream stormflows are too high. Model results indicate BMP implementation has the most pronounced effects on constituent EMCs at sites with the lowest ratio of upstream drainage area to highway catchment area. In contrast, BMP implementation has the most pronounced effects on mean annual load at sites with the largest highway catchment area (regardless of the upstream drainage area). For this scenario, it may be that the end-user needs to weigh the importance of keeping a specific number of river miles below water-quality criteria thresholds against the total amount of constituent being added and the potential for adverse effects from the additional loads downstream.

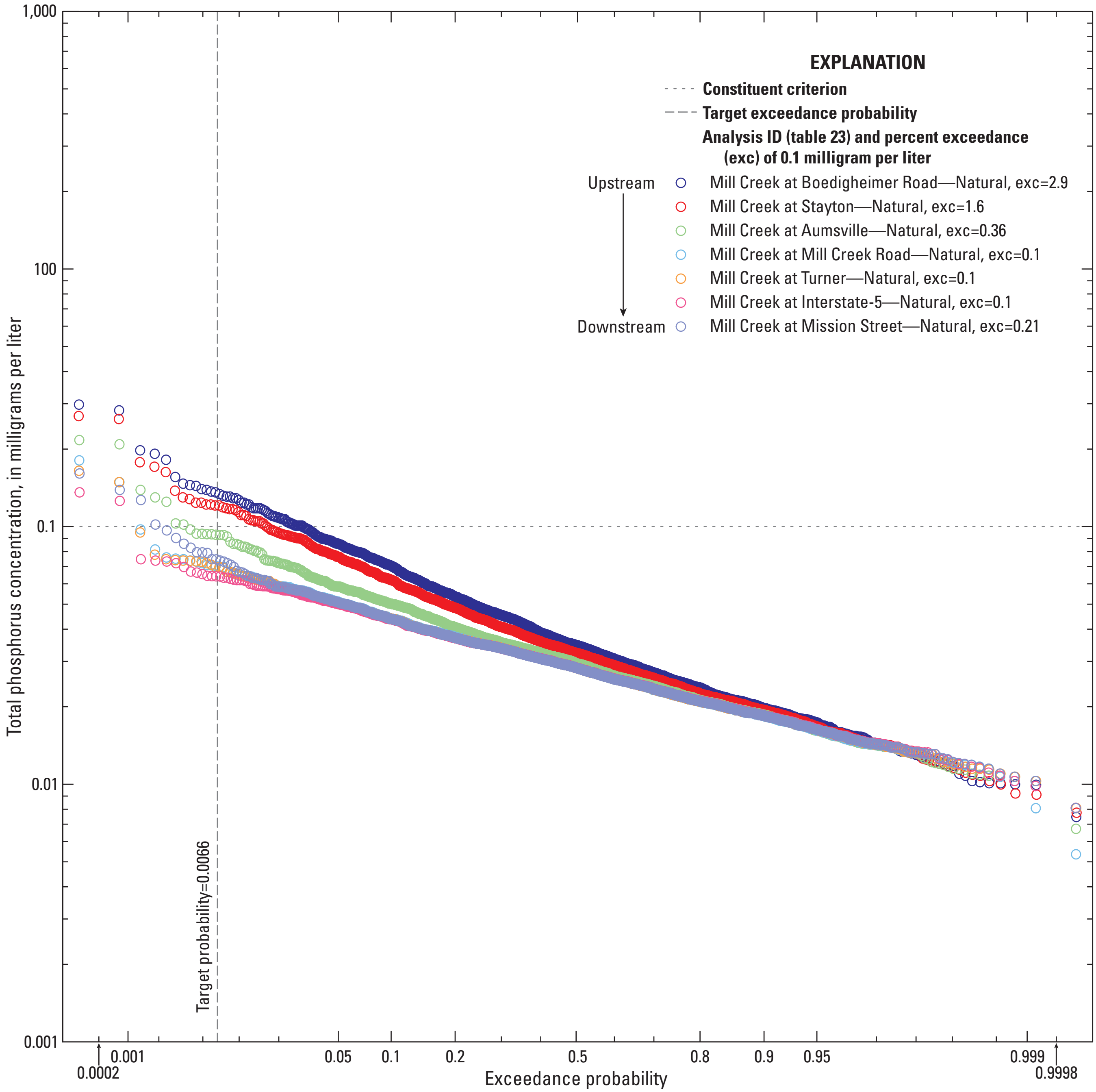



**Figure 24.** Downstream exceedance probabilities of total phosphorous under Simulation Scenario 1—Natural Conditions, with best management practice (BMP) implemented, at Mill Creek sites, Oregon.

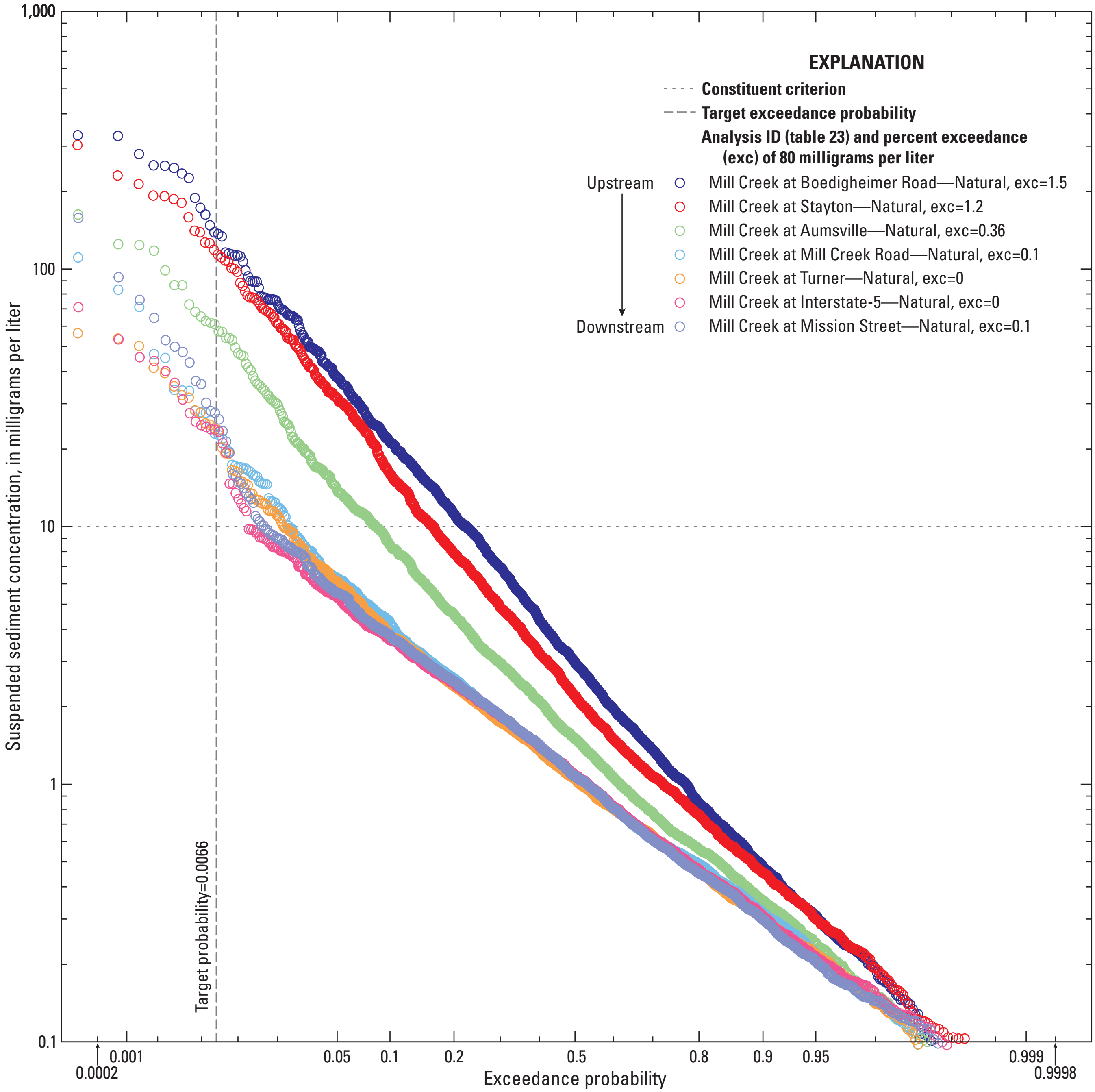



**Figure 25.** Downstream exceedance probabilities of suspended sediment under Simulation Scenario 1—Natural Conditions, with best management practice (BMP) implemented, at Mill Creek sites, Oregon.

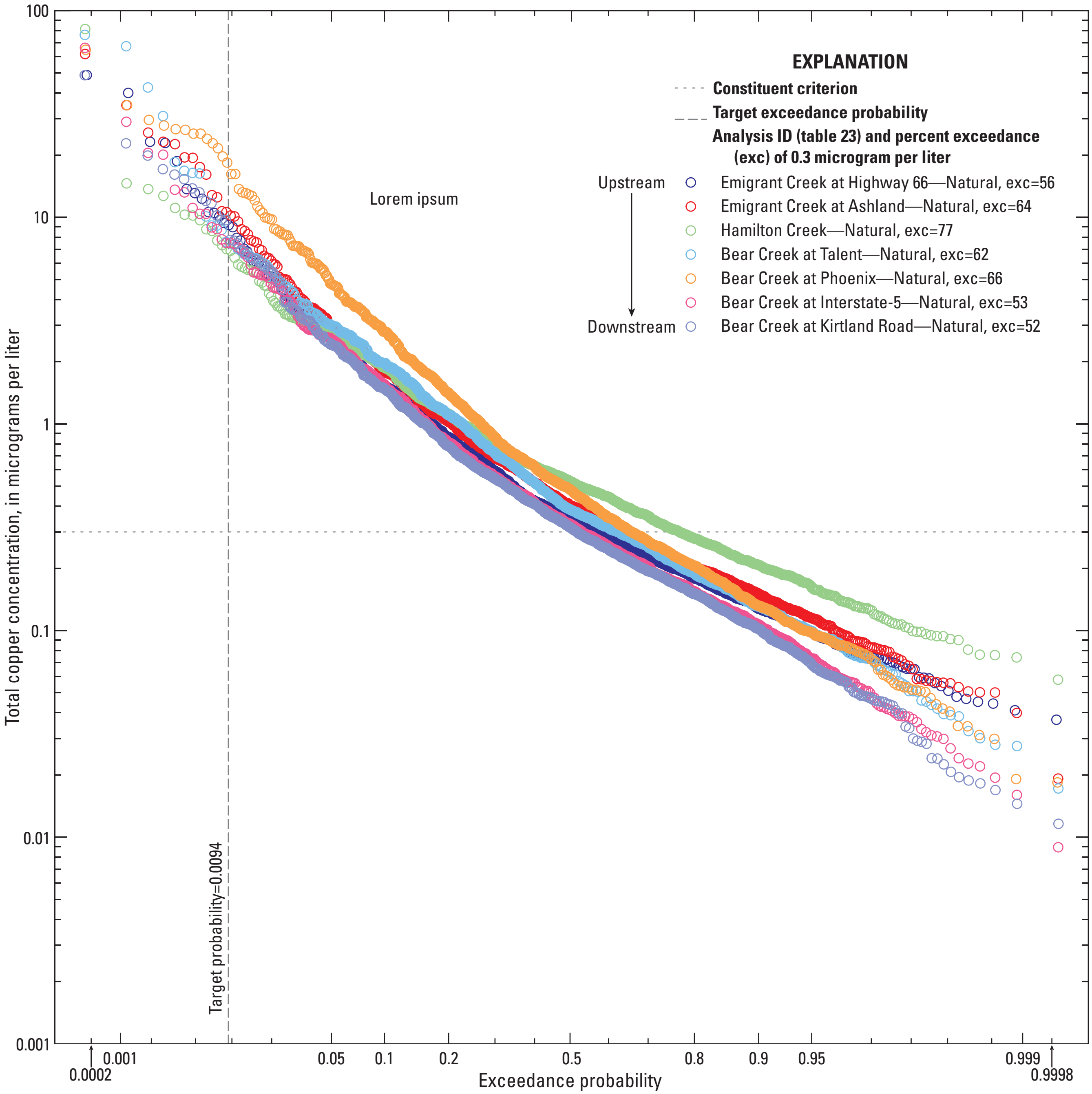



**Figure 26.** Downstream exceedance probabilities of total copper under Simulation Scenario 1—Natural Conditions, with best management practice (BMP) implemented, at Bear Creek sites, Oregon.

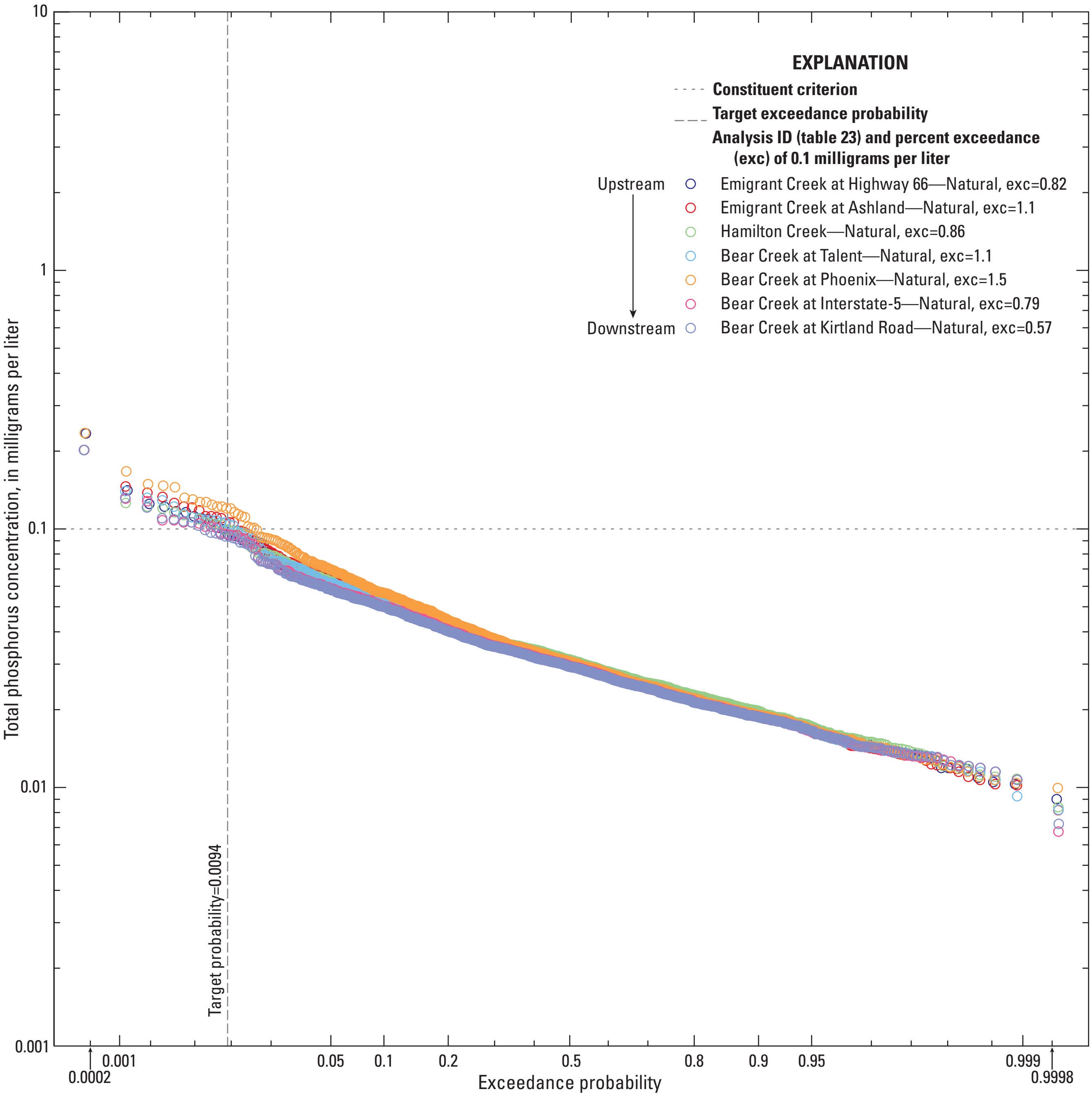



**Figure 27.** Downstream exceedance probabilities of total phosphorous under Simulation Scenario 1–Natural Conditions, with best management practice (BMP) implemented, at Bear Creek sites, Oregon.

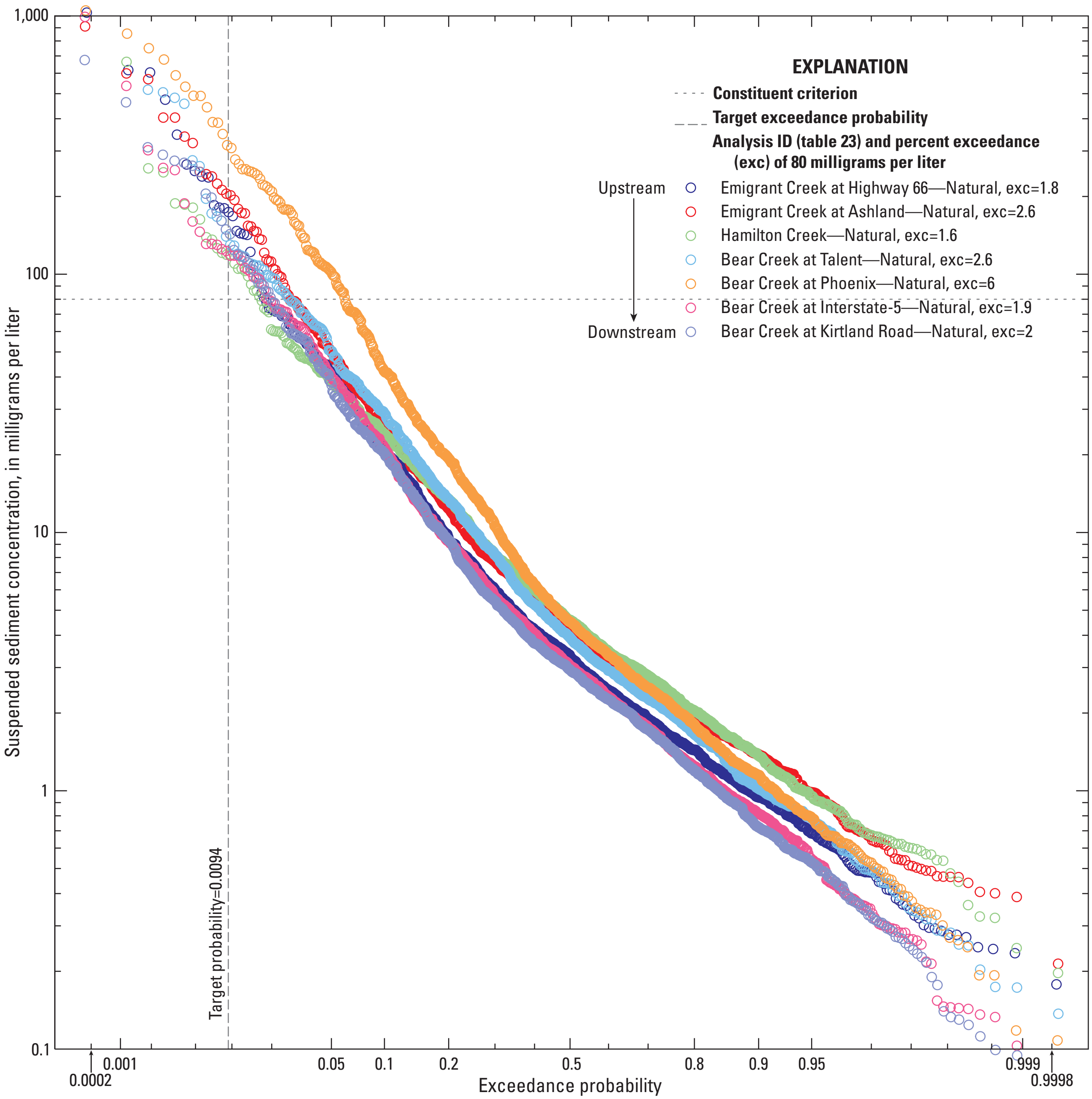



**Figure 28.** Downstream exceedance probabilities of suspended sediment concentration under Simulation Scenario 1—Natural Conditions, with best management practice (BMP) implemented, at Bear Creek sites, Oregon.

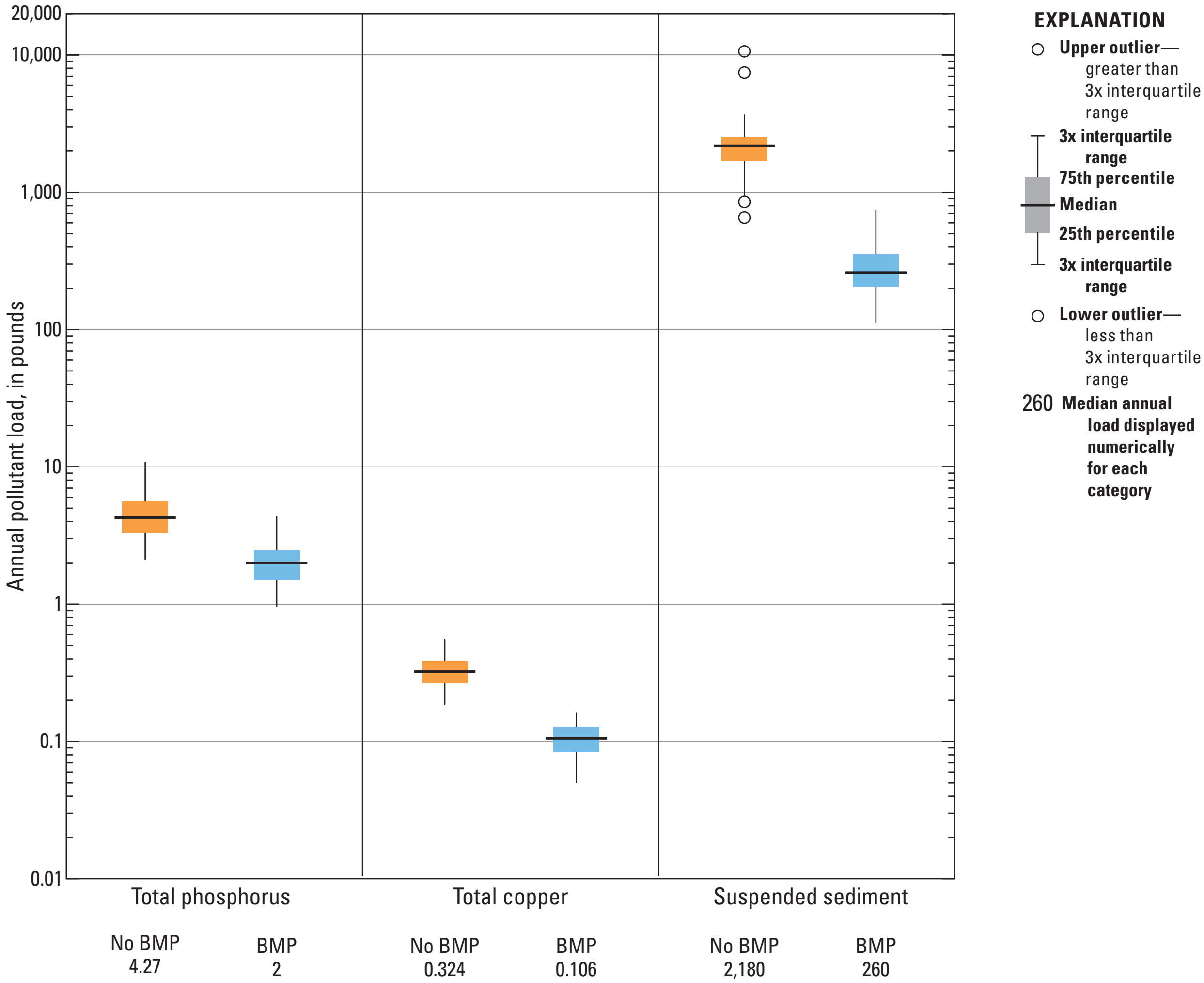



**Figure 29.** Median annual highway loads of total phosphorus, total copper, and suspended sediment under Simulation Scenario 1—Natural Conditions with and without best management practice (BMP) implementation, at Emigrant Creek at Highway 66 site, Bear Creek watershed, Oregon.

**Table 25.** Downstream median annual highway loading for Simulation Scenario 1—Natural Conditions, Bear and Mill Creek watersheds, Oregon.

[**Abbreviations:** BMP, best management practices; lb, pounds; SSL, suspended sediment load; TCu, total copper; TP, total phosophorus; %, percent]

| Site | SSL | | | TCu | | | TP | | |
|---|---|---|---|---|---|---|---|---|---|
| | No BMP (lb) | BMP (lb) | Reduc-tion(%) | No BMP (lb) | BMP (lb) | Reduc-tion(%) | No BMP (lb) | BMP (lb) | Reduction (percentage) |
| Bear Creek watershed | | | | | | | | | |
| Emigrant Creek at Highway 66 | 2,180 | 260 | 88 | 0.324 | 0.106 | 67 | 4.27 | 2 | 53 |
| Emigrant Creek at Ashland | 1,600 | 224 | 86 | 0.31 | 0.103 | 67 | 3.61 | 1.72 | 52 |
| Hamilton Creek | 217 | 34.7 | 84 | 0.042 | 0.014 | 67 | 0.523 | 0.254 | 51 |
| Bear Creek at Talent | 1,090 | 146 | 87 | 0.208 | 0.063 | 70 | 2.33 | 1.15 | 51 |
| Bear Creek at Phoenix | 1,900 | 267 | 86 | 0.344 | 0.107 | 69 | 4.535 | 2.135 | 53 |
| Bear Creek at Interstate-5 | 49.1 | 7.03 | 86 | 0.009 | 0.003 | 70 | 0.119 | 0.056 | 53 |
| Bear Creek at Kirtland Road | 108 | 12.75 | 88 | 0.018 | 0.006 | 69 | 0.226 | 0.107 | 53 |
| Mill Creek watershed | | | | | | | | | |
| Mill Creek at Boedigheimer Road | 3,450 | 474 | 86 | 0.581 | 0.184 | 68 | 7.44 | 3.4 | 54 |
| Mill Creek at Stayton | 6,450 | 966 | 85 | 1.27 | 0.39 | 69 | 15.6 | 7.28 | 53 |
| Mill Creek at Aumsville | 925 | 105 | 89 | 0.141 | 0.045 | 68 | 1.86 | 0.852 | 54 |
| Mill Creek at Mill Creek Road | 1,110 | 128 | 88 | 0.17 | 0.054 | 68 | 2.24 | 1.03 | 54 |
| Mill Creek at Turner | 1,370 | 189 | 86 | 0.231 | 0.073 | 68 | 2.96 | 1.35 | 54 |
| Mill Creek at Interstate-5 | 11,000 | 1,340 | 88 | 1.67 | 0.585 | 65 | 22.6 | 10.3 | 54 |
| Mill Creek at Mission Street | 274 | 32.8 | 88 | 0.043 | 0.015 | 66 | 0.591 | 0.272 | 54 |

## Simulation Scenario 2—Current Conditions

Simulation Scenario 2 was designed to represent current conditions that exist in the Bear and Mill Creek watersheds. This simulation was conducted in two parts—simulation scenarios 2A and 2B. In scenario 2A, the developed area runoff is simulated by using the SELDM highway module with the urban-runoff statistics, and combined with the undeveloped portion of the upstream drainage area. In scenario 2B, the output from scenario 2A is used to model the concurrent upstream stormflows and EMCs, and the highway runoff is added as usual based on current conditions.

Figures 30–32 show schematics for Simulation Scenario 2. The initial model setup (fig. 30) is similar to scenario 1 (fig. 11), except there are now multiple areas labeled as "developed." The amount of developed area was estimated using the fraction of impervious area output from StreamStats. In Simulation Scenario 2A, there is no highway. Instead, the developed areas are used in place of the highway (fig. 31). This had the effect of concentrating the developed area into a point source of runoff, rather than distributed over a larger area. The resulting output from scenario 2A is then used as the upstream input in scenario 2B (fig. 32), and the highway runoff is applied as normal.

Simulation Scenario 2 represents conservative estimates of constituent EMCs. Conversely to how modeled in simulation 2A, the developed portion of an upstream basin does not all at once flow into a watershed just upstream from the crossing, but instead flows into a watershed in a more distributed-manner, usually from relatively close to a stream where development tends to occur. SELDM is a lumped parameter model rather than a distributed watershed model. Because average storm durations are on the order of 10 hours, compounding the developed areas as a discharge upstream from the highway site without instream processing represents a conservative estimate of upstream water-quality for the highway simulations. In other words, the modeled EMCs are expected to be slightly higher than what would be observed because the configuration of this simulation does not allow for attenuation of developed-area runoff into the stream, which would result in a more even distribution of water-quality constituent loads over time. Efforts to simulate the effects of individual runoff discharges from a distributed set of developed areas may be feasible for small watersheds with relatively few input sources from such developed areas, but not for the larger watersheds evaluated in this study. Furthermore, because there are large uncertainties involved in estimating every statistic used in any stormwater simulation, use of a complex watershed model may give the false appearance of greater accuracy and precision. Unless there is a large, level-three data-collection effort to support site calibration, the perceived accuracy and precision may be illusory because complex models can provide worse results than simpler models if the complex models are not properly calibrated (Zarriello, 1998; Cooperative Research Center for Catchment Hydrology, 2005).

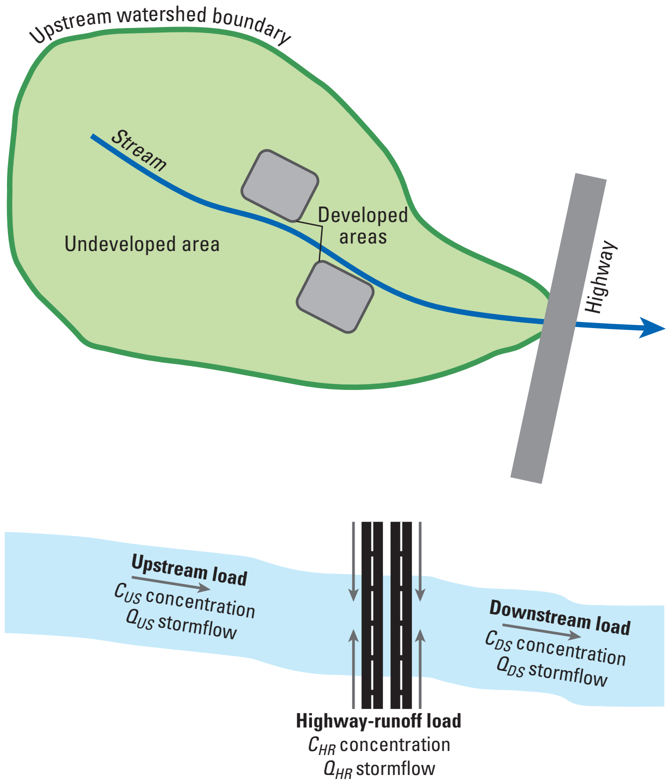



**Figure 30.** Diagram 1 of Stochastic Empirical Loading and Dilution Model Simulation Scenario 2A. (*CDS*, concentration of upstream load; *CHR*, concentration of highway-runoff load; *CUS*, concentration of upstream load; *QDS*, stormflow downstream load; *QHR*, stormflow of highway-runoff load; *QUS*, stormflow of upstream load)

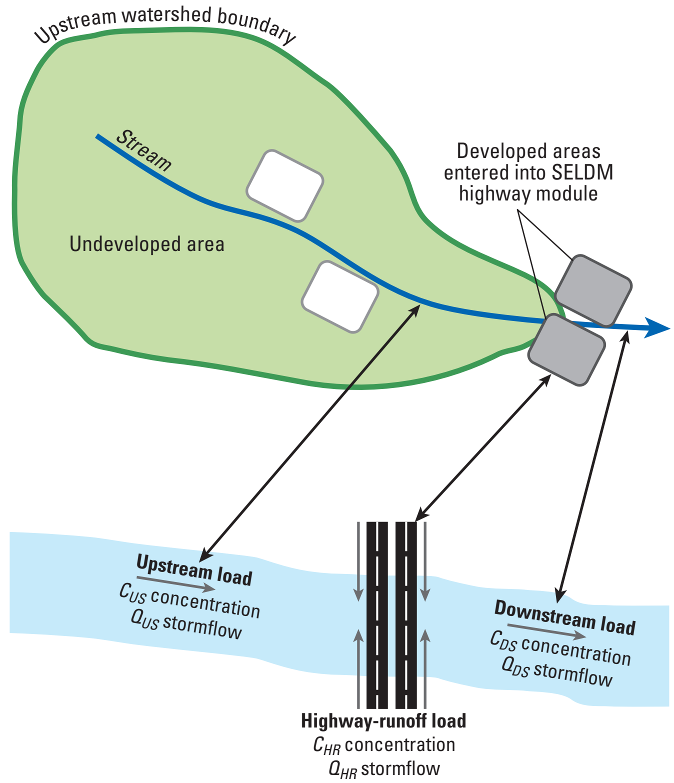



**Figure 31.** Diagram 2 of Stochastic Empirical Loading and Dilution Model Simulation Scenario 2A. (*CDS*, concentration of upstream load; *CHR*, concentration of highway-runoff load; *CUS*, concentration of upstream load; *QDS*, stormflow downstream load; *QHR*, stormflow of highway-runoff load; *QUS*, stormflow of upstream load)

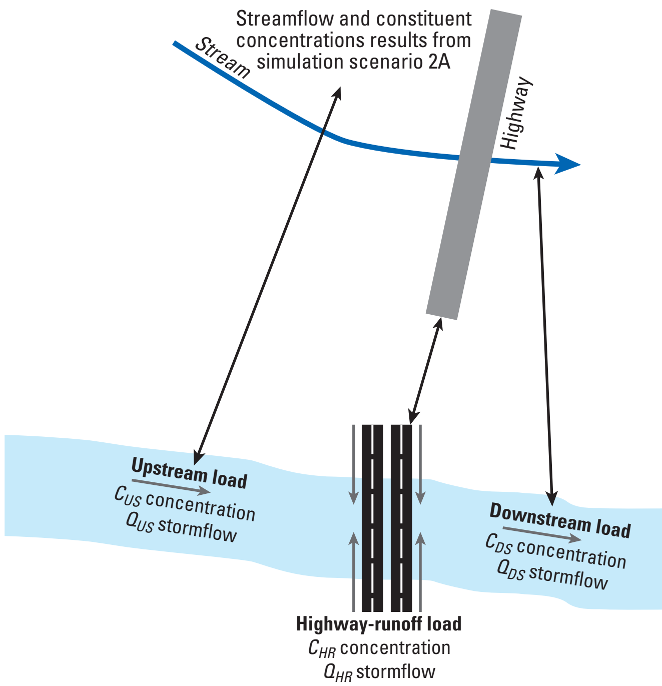



**Figure 32.** Diagram of Stochastic Empirical Loading and Dilution Model Simulation Scenario 2B. (*CDS*, concentration of upstream load; *CHR*, concentration of highway-runoff load; *CUS*, concentration of upstream load; *QDS*, stormflow downstream load; *QHR*, stormflow of highway-runoff load; *QUS*, stormflow of upstream load)

## Runoff-Quality Risk Analysis

Model results from Simulation Scenario 2A indicate that EMCs of concurrent downstream stormflow are higher at some sites relative to Simulation Scenario 1. Returning to the previous Simulation Scenario 1 example of Emigrant Creek at Highway 66, model results estimate the risk of any given storm exceeding a downstream TP EMC of 0.1 mg/L for Simulation Scenario 2 is about 20 percent (fig. 33), which is substantially higher than the same result for Simulation Scenario 1 (about 1 percent, fig. 12). In addition, the population of downstream EMCs has much higher concentrations than the upstream EMCs, which is in contrast to what was observed in Simulation Scenario 1 (fig. 12), where the two populations plotted closely. This is a result of the total upstream developed area being much larger than the area for any given highway catchment at the crossing. For Simulation Scenario 2B, which represents the output from 2A plus the highway, the upstream, and downstream EMCs once again plot closely together (not shown).

Model results from Simulation Scenario 2B indicate all of the sites in the Bear Creek watershed would have more exceedances of the TP criterion with more development upstream (fig. 34). This is to be expected, as the mean TP runoff concentration used for developed areas (approximately 2.48 mg/L) is typically much higher than the concurrent upstream stormflow TP concentration modeled using transport curves for undeveloped conditions (table 21). For example, using the median flow at the Emigrant Creek at Highway 66 site, the transport curve yields a mean TP EMC of 0.03 mg/L. Hamilton Creek indicates the highest probability of exceedance (79 percent; fig. 34), which is expected given its relatively small upstream drainage area and large developed area runoff contribution (modeled as highway in SELDM).

TP results from modeled Simulation Scenario 2B for the Mill Creek watershed (fig. 35) were similar to those of Bear Creek (fig. 34). The rate of TP exceedances of the 0.1-mg/L criterion increased compared to Simulation Scenario 1 at all sites. However, modeled increases in exceedance frequencies were small for those sites with relatively little upstream development (Mill Creek at Boedigheimer Road and Mill Creek at Stayton have only 12 and 32 acres of developed area upstream, respectively [table 23]). The rates of exceedances tended to increase with increasing drainage area and total impervious area (TIA). The most downstream site (Mill Creek at Mission Street) displayed the highest rate of exceedance (51 percent).

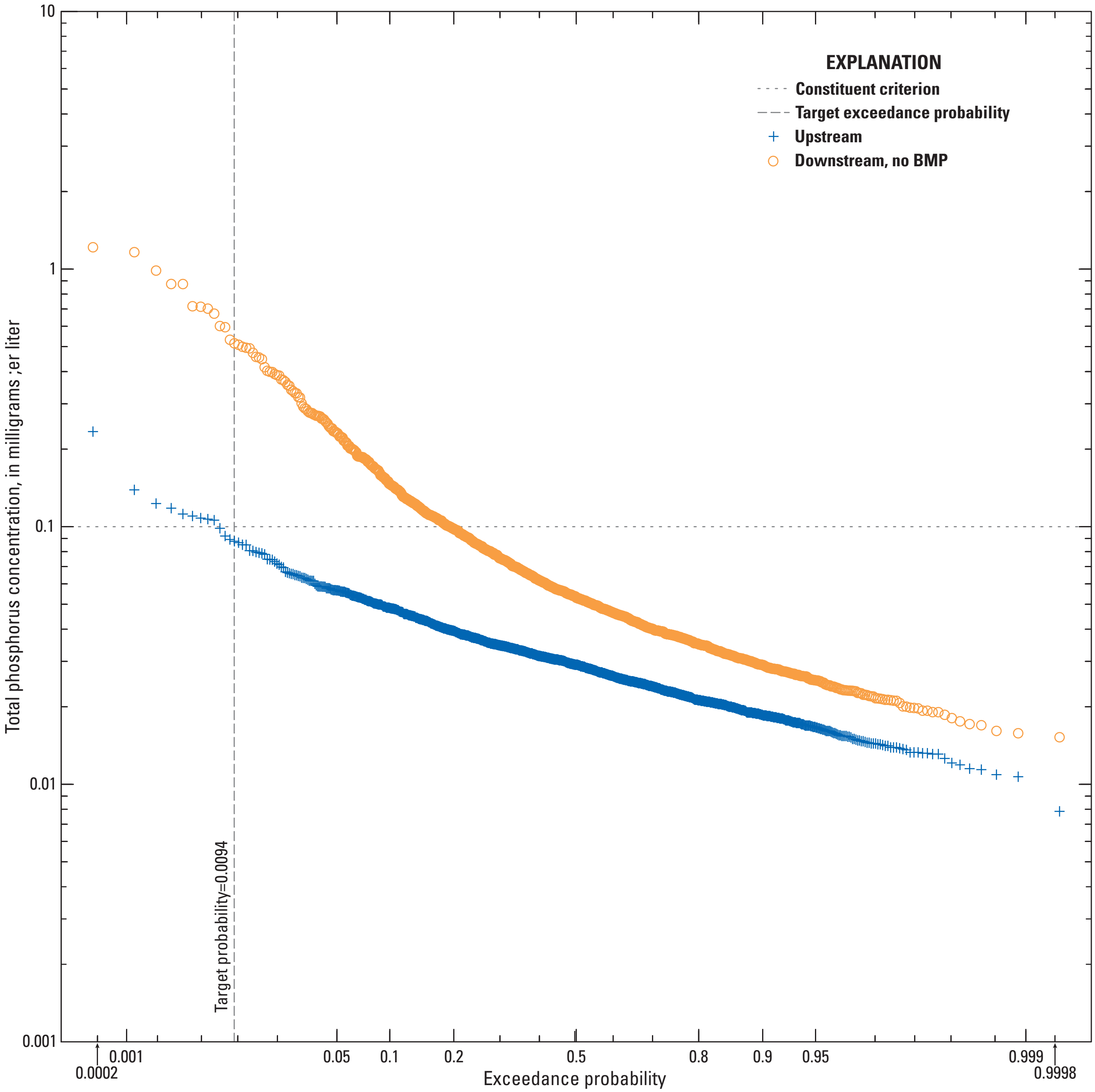



**Figure 33.** Exceedance probabilities of total phosphorus concentration upstream and downstream under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area) with no best management practices (BMP) implemented, at Emigrant Creek at Highway 66 site, Bear Creek, Oregon.

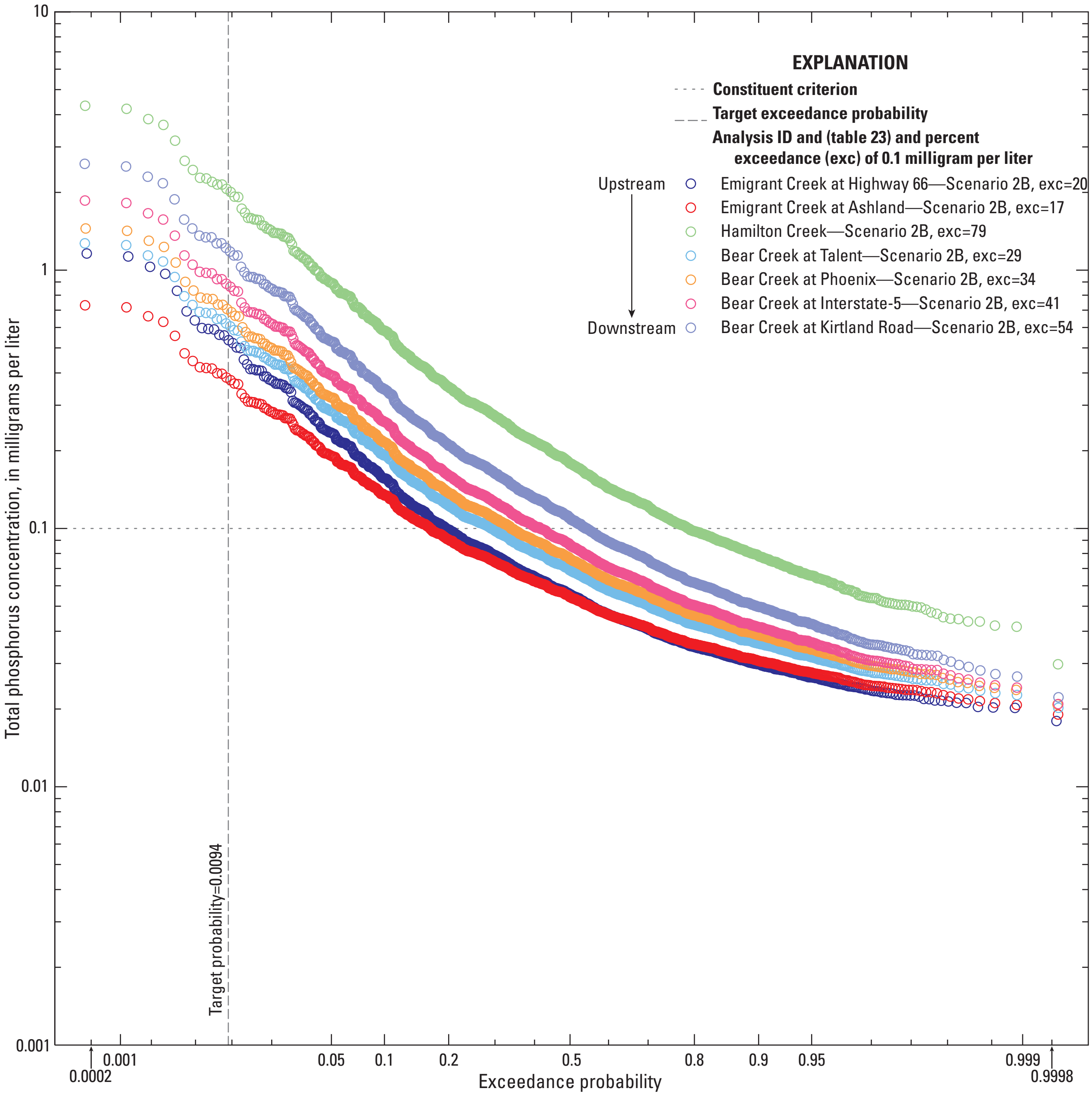



**Figure 34.** Downstream exceedance probabilities of total phosphorous under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with no best management practices (BMP) implemented, at Bear Creek sites, Oregon.

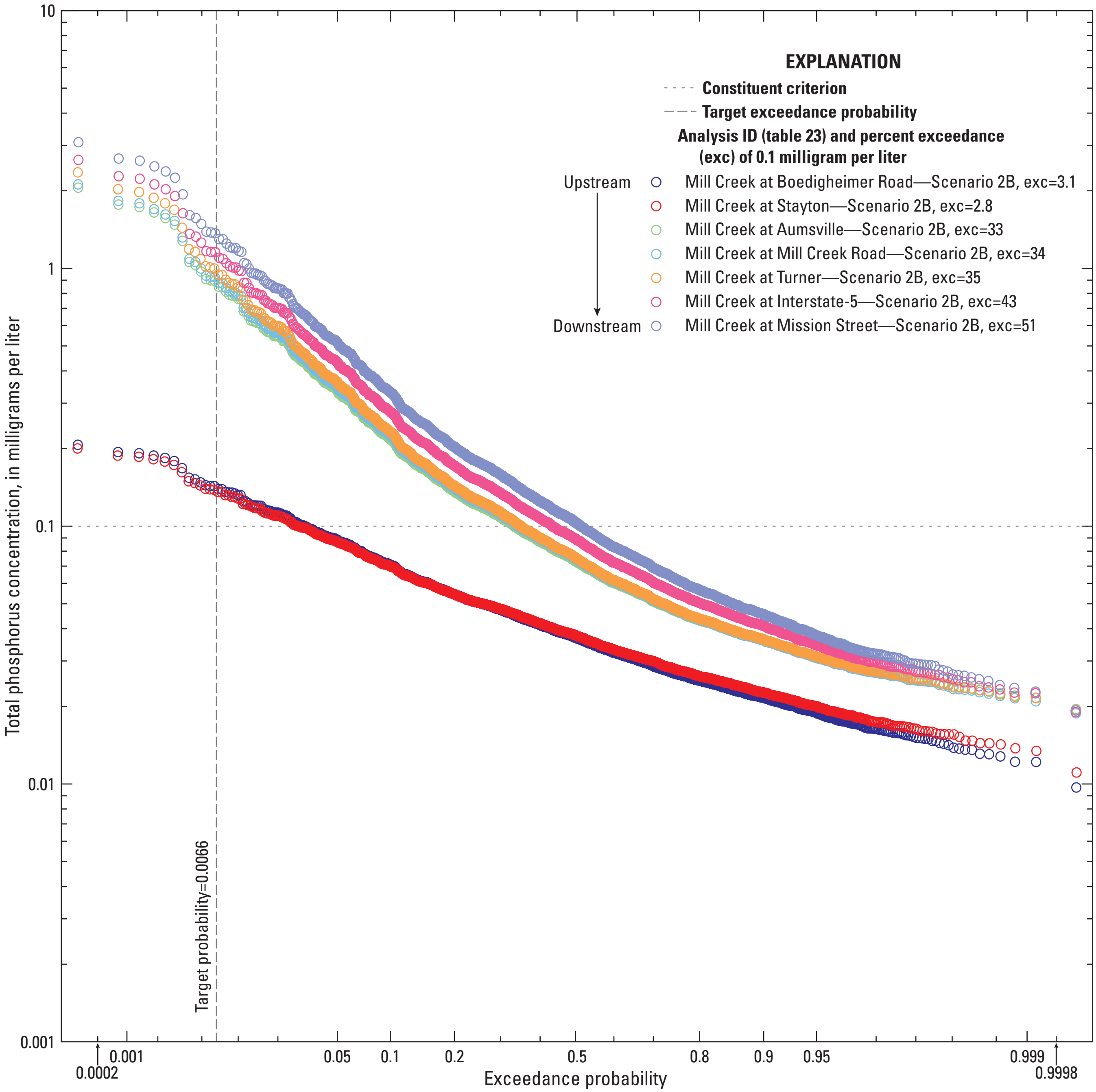



**Figure 35.** Downstream exceedance probabilities of total phosphorous under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with no best management practices (BMP) implemented, at Mill Creek sites, Oregon.

The TCu results for Simulation Scenario 2B indicated that almost all (97 percent) runoff events produce water-quality exceedances above the 0.3-µg/L TCu threshold, and exceedances will be common for any watershed with upstream development and no BMPs in place. Model results indicate that in the Bear Creek watershed (fig. 36), all but the most upstream site, Emigrant Creek at Highway 66, indicate exceedances in greater than 99.9 percent of runoff events. In the Mill Creek watershed (fig. 37), model results for the two most upstream sites indicate exceedance probabilities between 62 and 72 percent, whereas the five sites downstream ranged from 98 to more than 99.9 percent of storm events.

A detailed evaluation of the site with the least chance of TCu exceedance in either watershed (Mill Creek at Boedigheimer Road) indicates the upstream EMCs of TCu commonly exceed the TCu criteria before either the developed area or the highway is accounted for ("upstream" curve, fig. 38). These results indicate that achieving this particular criteria would be difficult if not impossible because of high background levels of copper.

The SSC results for Simulation Scenario 2 in the Bear Creek (fig. 39) and Mill Creek (fig. 40) watersheds indicate that, relative to Simulation Scenario 1, the greatest increases in exceedance probabilities of the 80-mg/L SSC criterion occurred in the most developed watersheds. In the Bear Creek watershed, this was again most evident at the Hamilton Creek site (28 percent probability of exceedance in Simulation Scenario 2B, compared to 2.9 percent in Simulation Scenario 1). In the Mill Creek watershed, the most developed site (Mill Creek at Mission Street) also had the greatest increase in exceedance probability from Simulation Scenario 1 to 2 (from 0.1 to 9.2 percent).

## Runoff Treatment Analyses

Because Simulation Scenario 2 involves two simulation steps, it allows for two different methods for interpreting runoff treatment analysis. Implementing a BMP for Simulation Scenario 2A was used as a way of determining the effect of treating all impervious surface runoff. Although such a practice is likely impractical and cost-prohibitive, modeling such an approach demonstrates the upper bounds of what EMC reductions are theoretically possible. In other words, any attempts made to reduce EMC values below the results from scenario 2A are not likely to be effective. Calculating this potential upper bound on EMC reductions may provide information needed to allocate resources for the construction and maintenance of BMPs in these cases. By contrast, implementing a BMP for Simulation Scenario 2B allows for a more straightforward analysis of runoff treatment only for the road crossing at the site.

Model results indicate substantial decreases in constituent EMCs for full impervious area BMP implementation in Simulation Scenario 2A. For example, the mean TCu EMC of downstream concurrent stormflow at the Mill Creek at Mission Street site decreases from 4.69 µg/L without BMP implementation to 1.34 µg/L with BMP implementation (fig. 41). This large difference in EMCs is a result of the disparity between developed area runoff, developed area runoff treated with a BMP, and the concurrent upstream stormflow EMCs (12.6, 5.94 and 0.237 µg/L, respectively, fig. 42). Sites with less upstream developed area had smaller differences between concurrent downstream stormflow EMCs with and without BMP implementation, but were more likely to have larger reductions in TCu criterion exceedance probabilities (figs. 43, 44). For example, while the mean EMC at the Mill Creek at Stayton site dropped from 0.778 µg/L without BMP implementation to 0.647 µg/L with implementation (data not shown), this decrease was enough to reduce the probability of a TCu criterion exceedance from 66 to 48 percent. Conversely, the more pronounced decreases in Simulation Scenario 2A in TCu EMCs at the Mill Creek at Mission Street site were not large enough to achieve a notable decrease in exceedance probabilities (storms exceeded the criterion 94 percent of the time with BMP implementation).

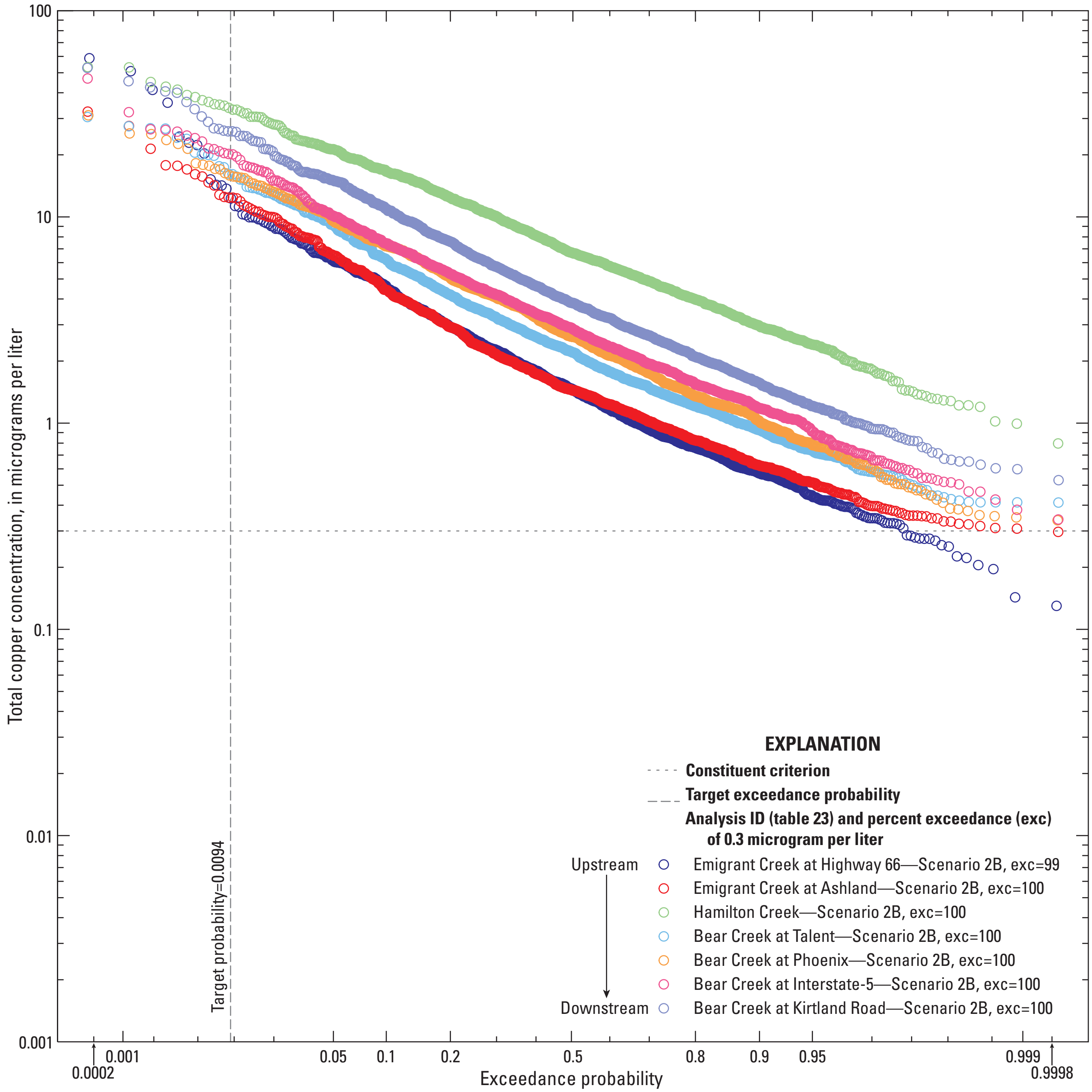



**Figure 36.** Downstream exceedance probabilities of total copper under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with no best management practices (BMP) implemented, at Bear Creek sites, Oregon.

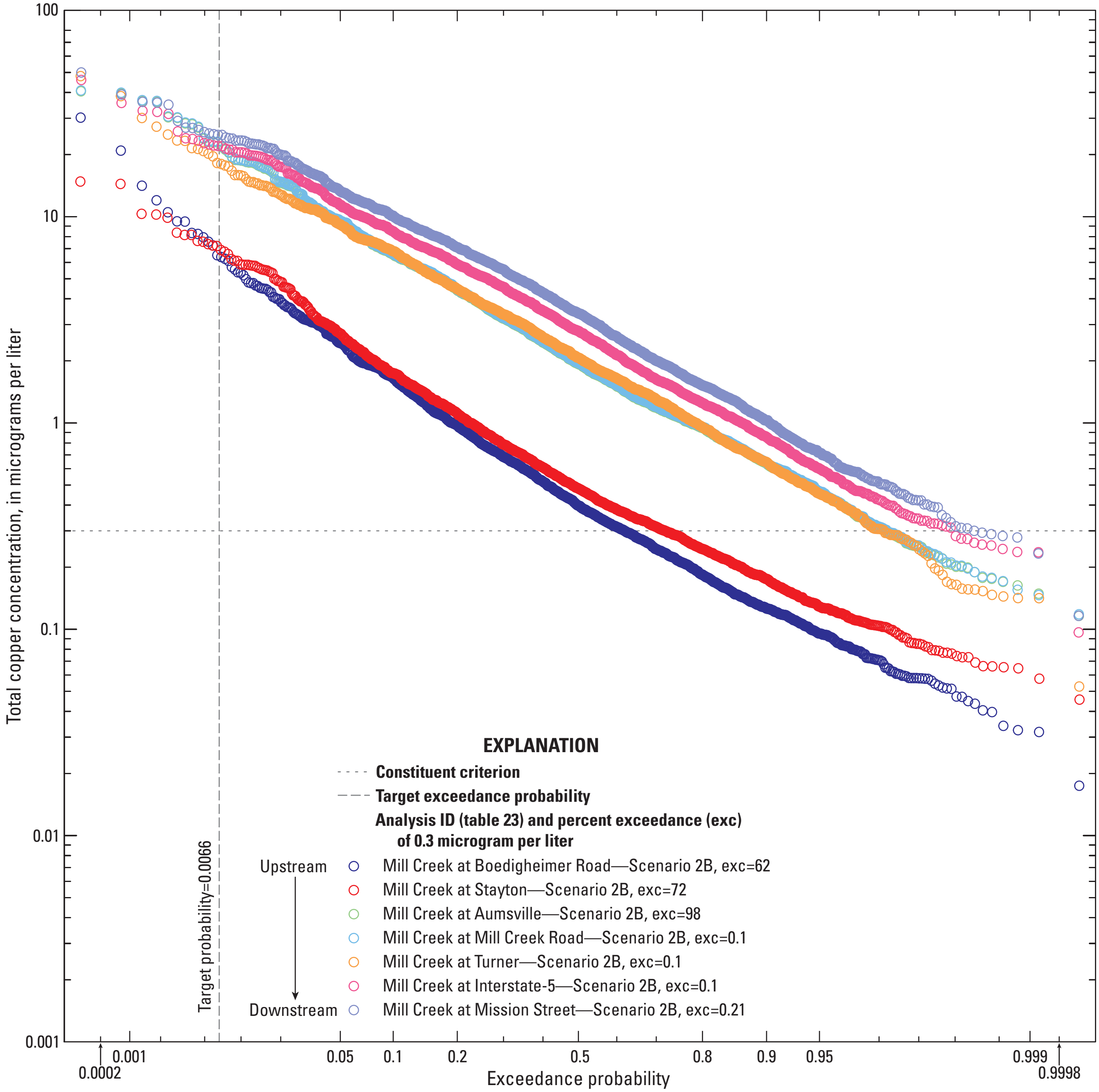



**Figure 37.** Downstream exceedance probabilities of total copper under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with no best management practices (BMP) implemented, at Mill Creek sites, Oregon.

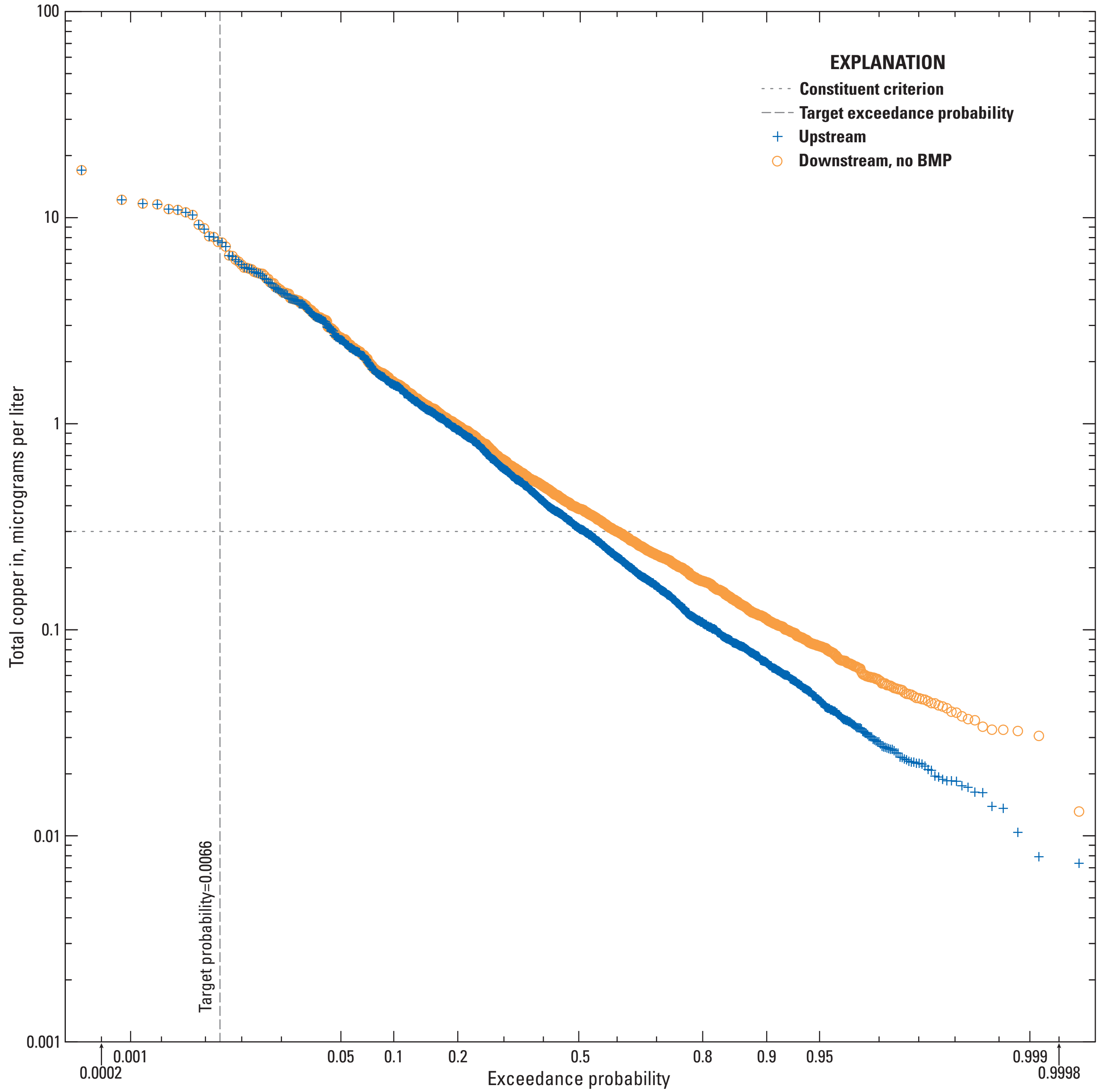



**Figure 38.** Exceedance probabilities of total copper concentration upstream and downstream from the road crossing under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area) with no best management practices (BMP) implemented, Mill Creek at Boedigheimer Road site, Mill Creek, Oregon.

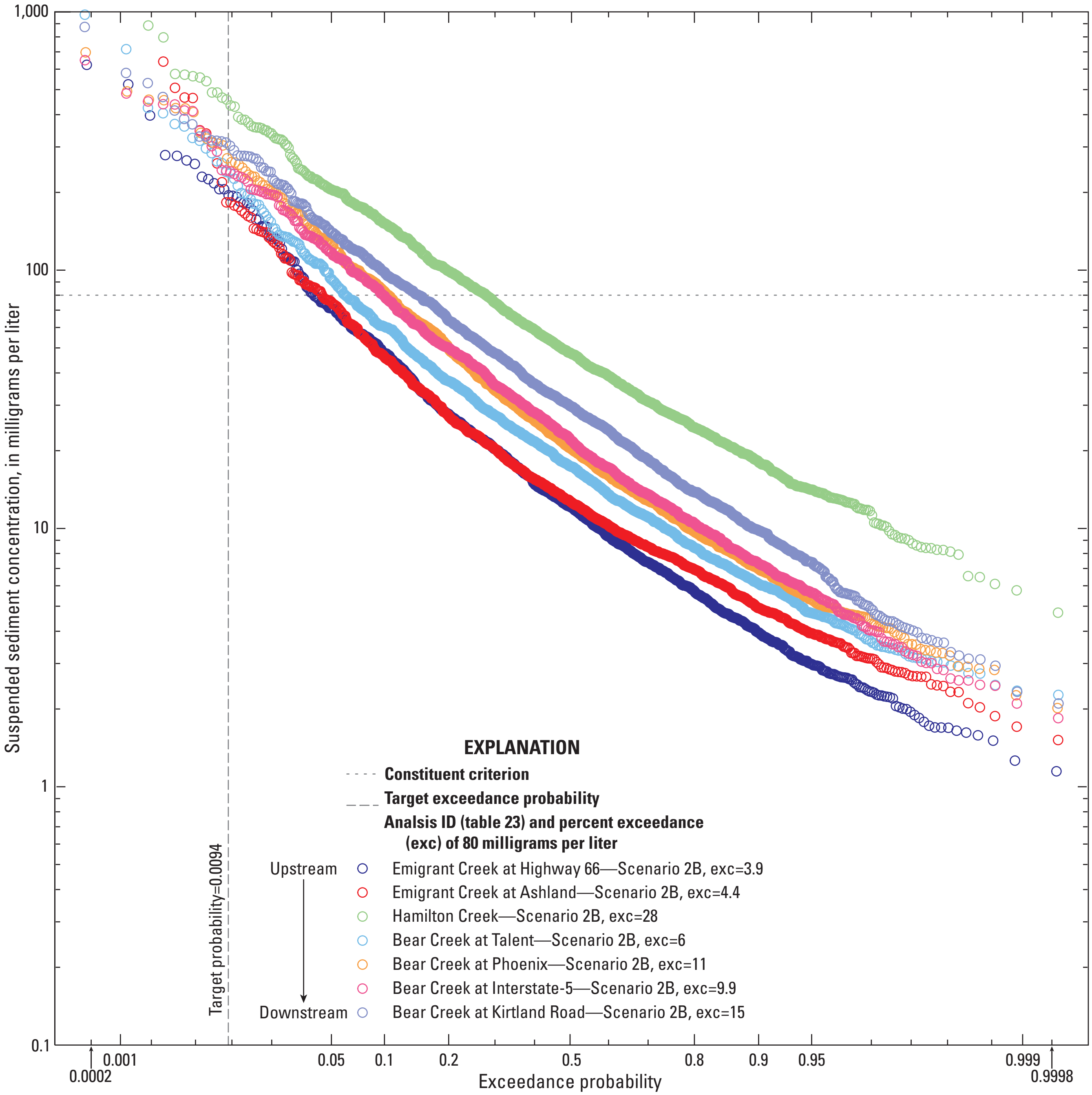



**Figure 39.** Downstream exceedance probabilities of suspended sediment under Simulation Scenario 2B —Current Conditions (developed area + undeveloped area + highway) , with no best management practices (BMP) implemented, at Bear Creek sites, Oregon.

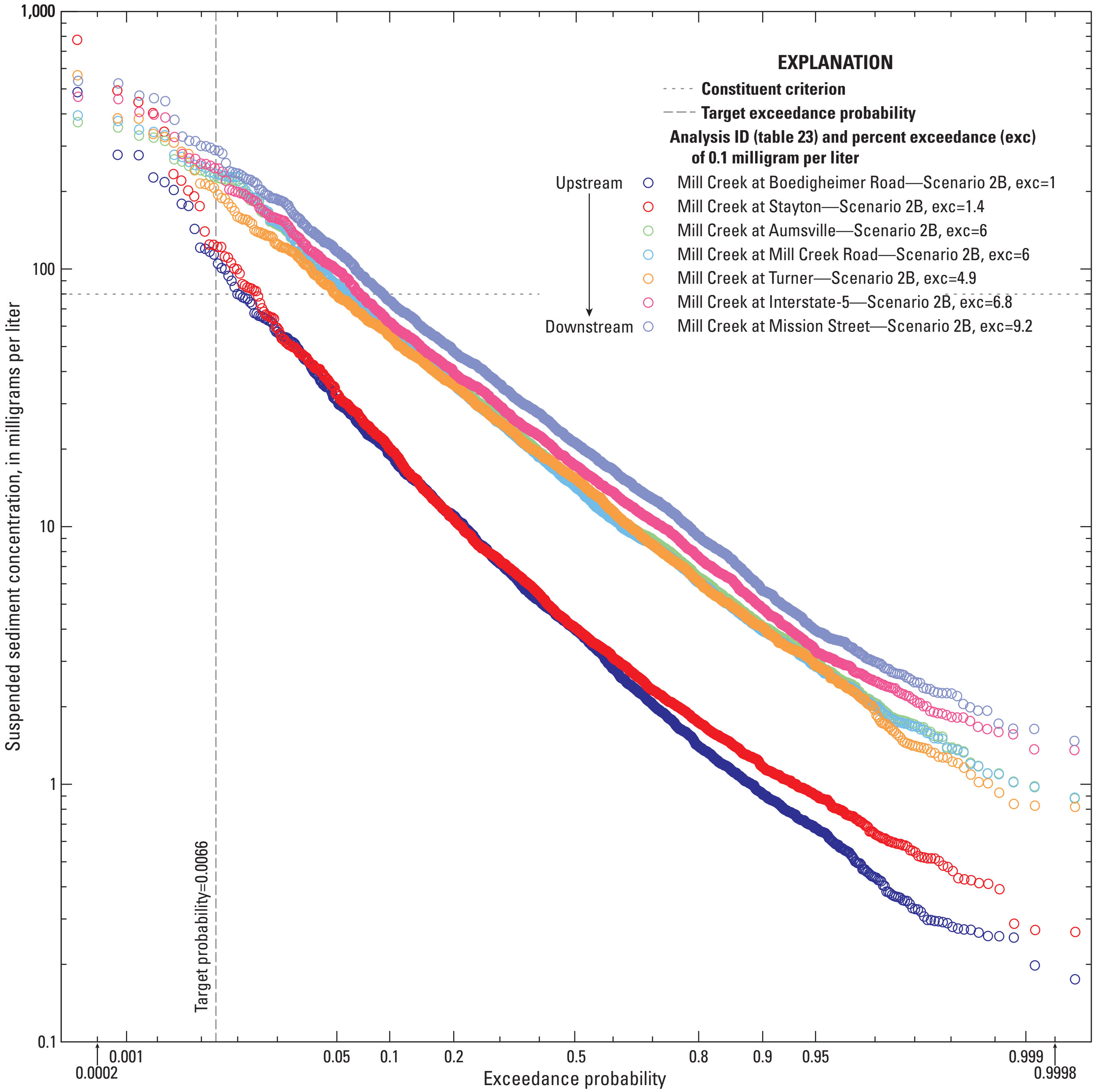



**Figure 40.** Downstream exceedance probabilities of Suspended Sediment under Simulation Scenario 2B —Current Conditions (developed area + undeveloped area + highway) , with no best management practices (BMP) implemented, at Mill Creek sites, Oregon.

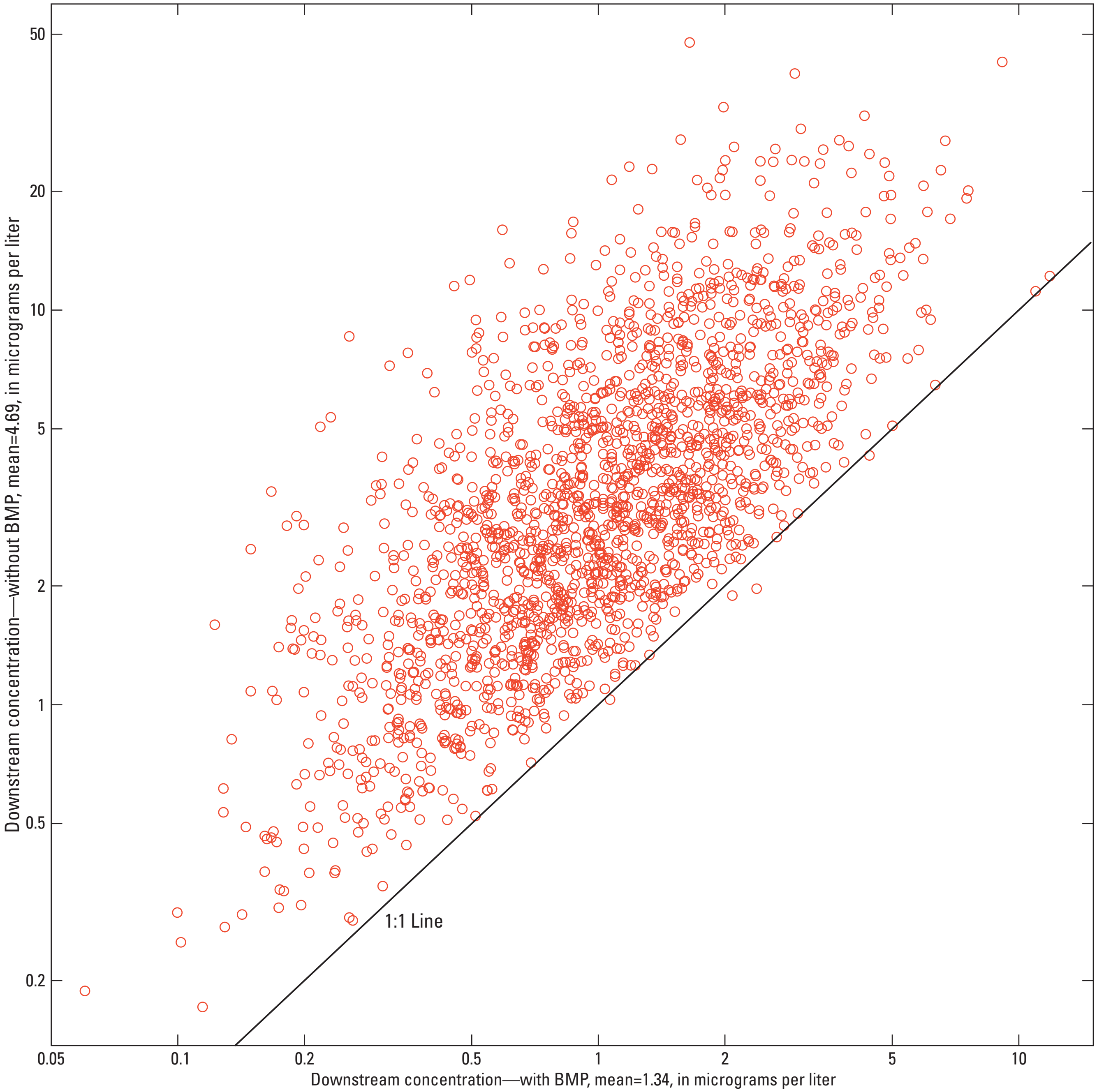



**Figure 41.** Downstream concentrations of total copper in micrograms per liter with and without best management practices (BMP) implementation for Simulation Scenario 2A—Current Conditions at Mission Street crossing of Mill Creek, Oregon.

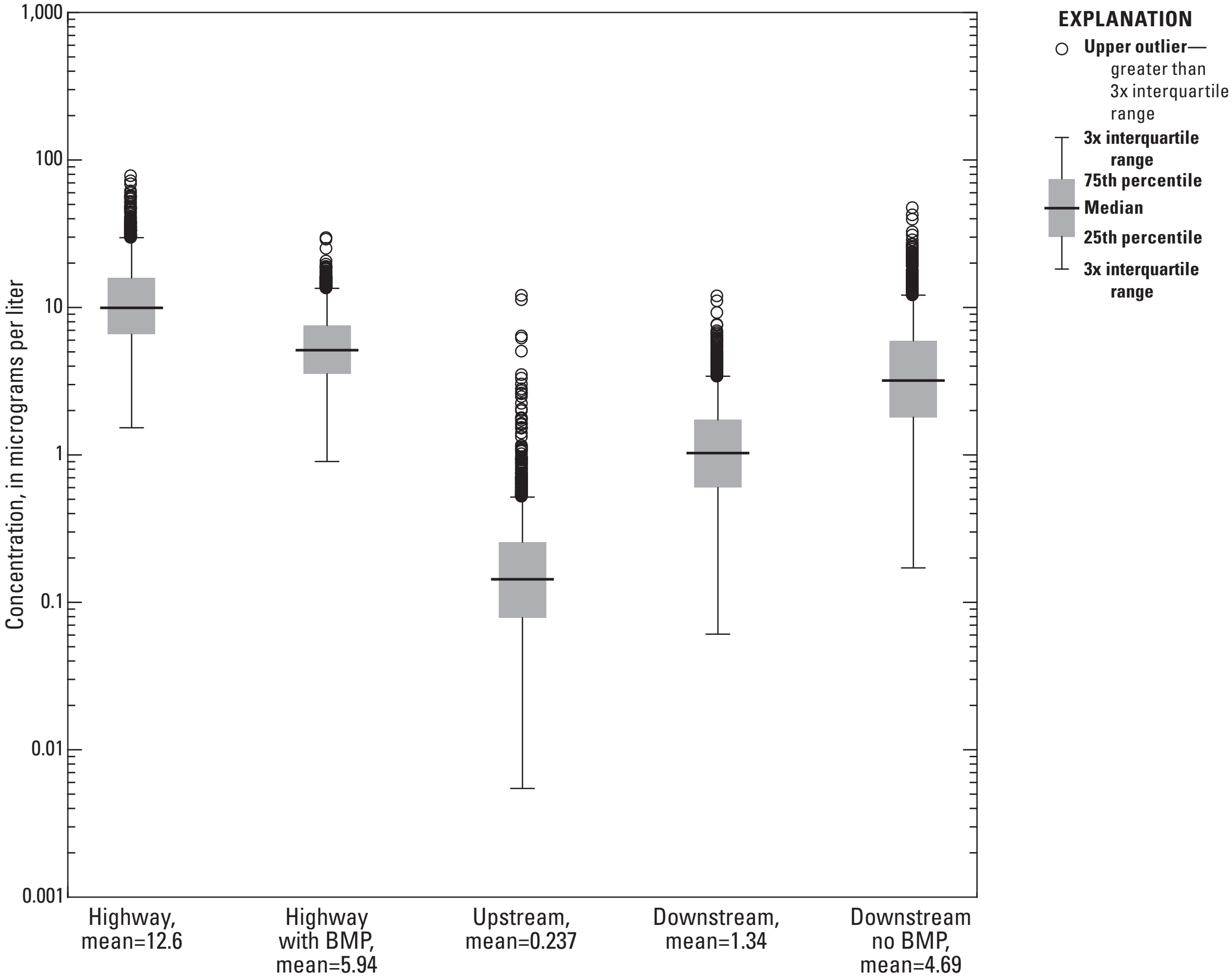



**Figure 42.** Upstream, and downstream concentrations of total copper with and without best management practices (BMP) implementation for Simulation Scenario 2A—Current Conditions (developed area + undeveloped area) at Mission Street crossing of Mill Creek, Oregon.

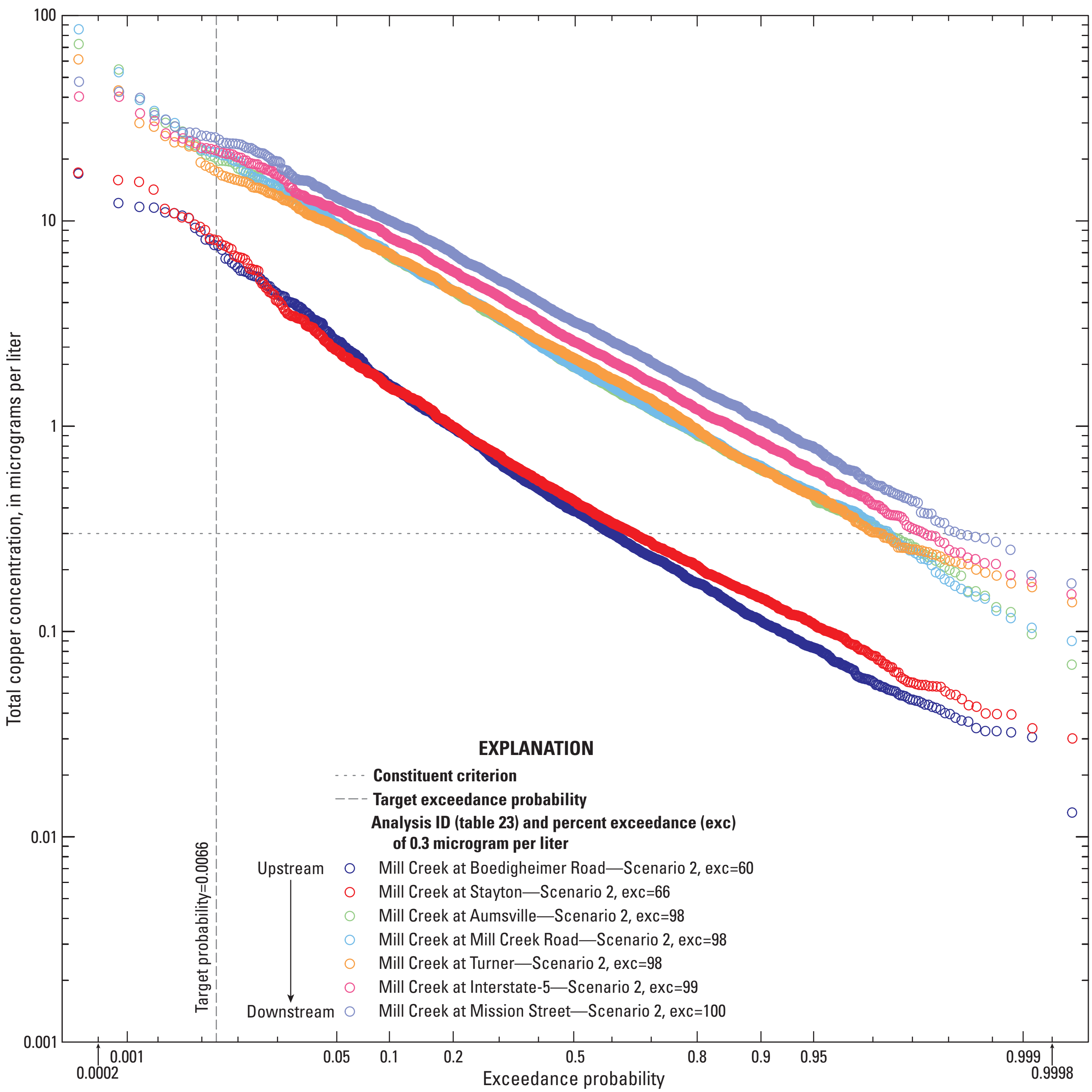



**Figure 43.** Downstream exceedance probabilities of total copper under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area), with no best management practices (BMP) implemented, at Mill Creek sites.

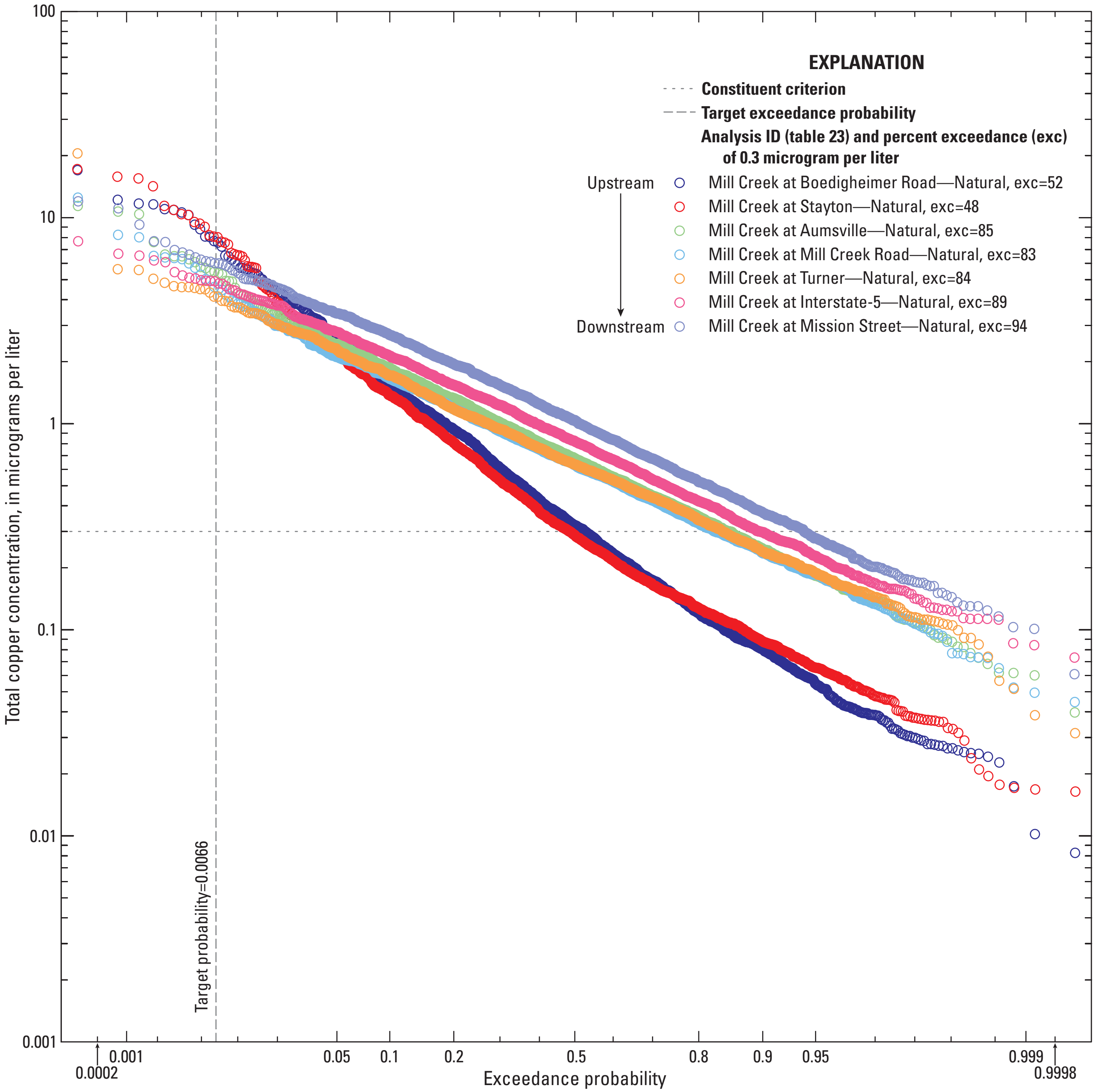



**Figure 44.** Downstream exceedance probabilities of total copper under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area), with best management practices (BMP) implemented, at Mill Creek sites.

Model results from implementation of a highway-area BMP at the road crossing for Simulation Scenario 2B indicate much smaller decreases in TCu EMCs, which is to be expected given the much smaller area being treated by the BMP. Returning to the Mill Creek at Mission Street example, BMP implementation indicates no appreciable decrease in concurrent downstream stormflow EMC, or even relative to the concurrent upstream stormflow mean EMC (figs. 45and 46).

Modeled TCu results for simulation scenarios 2A and 2B were similar in the Bear Creek watershed. As would be expected, the largest decreases in TCu EMCs from BMP implementation in Simulation Scenario 2A occurred at Hamilton Creek (fig. 47). Overall decreases in EMCs from BMP implementation were greatest for sites with the largest percentage of impervious area (fig. 48, table 26). Similar to the BMP implementation in the Mill Creek watershed, BMP implementation in the Bear Creek watershed under Simulation Scenario 2B resulted in small or negligible differences in concurrent downstream stormflow EMCs (figs. 49 and 50).

For Bear and Mill Creek watersheds, the other two water-quality constituents (TP and SSC) evaluated resulted in similar findings to what was observed by evaluating TCu simulation results. Modeled implementation of BMPs resulted in the largest decreases in EMCs at locations with the smallest ratios of upstream drainage area to highway or developed area runoff drainage area. And, all reductions in EMC were much greater for Simulation Scenario 2A than 2B.

One difference between the TCu results and the results of the other water-quality constituents is the effectiveness of reducing the probability of exceeding the criterion for any given storm. Because the TCu EMCs of concurrent upstream stormflow are high relative to the criteria, BMP implementation at sites results in little if any decrease in the probability of exceedance. Conversely, SSC and TP EMCs of concurrent upstream stormflow are not as high relative to their criteria, so BMP implementation often results in marked decreases in criterion exceedance probabilities. For example, in Simulation Scenario 2A, model results indicate the implementation of a BMP at the Hamilton Creek site reduces the probability of a SSC exceedance from 27 (fig. 51) to 1.6 percent (fig. 52). The latter value is almost low enough to meet the target goal of only one exceedance every 3 years (0.93 percent for Hamilton Creek).

## Runoff-Quality Annual Load Analyses

Similar to Simulation Scenario 1, modeled median annual developed area loads of SS, TCu, and TP were highly correlated with the amount of impervious developed area (highway area in Simulation Scenario 1) (tables 26 and 27). Returning to the example of Emigrant Creek at Highway 66, modeled annual loading of SS, TCu, and TP are much larger in Simulation Scenario 2A compared to Simulation Scenario 1 (tables 25 and 26, fig. 53). For example, the modeled median annual load of TCu at the Highway 66 crossing increased from 0.324 to 6.53 lb between simulation scenarios 1 and 2A (figs. 29 and 53, respectively), assuming no BMP implementation. This is expected given the higher levels of TCu runoff from developed areas relative to undeveloped areas and the much larger areas contributing to urban runoff upstream from the road crossing. The difference between the two scenarios is greater for sites with large developed areas upstream. At the Bear Creek at Kirtland Road site, modeled median annual TCu load increased from 0.018 (table 25) to 509 pounds (table 26) between simulation scenarios 1 and 2A, assuming no BMP implementation. Simulation Scenario 2B median annual highway loads are similar to values from Simulation Scenario 1 as the contributing areas to highway runoff are identical, whereas the developed area modeled in scenario 2A (instead of a highway) is much larger than in scenario 2B.

By analyzing loading from the two phases of Simulation Scenario 2, it is possible to estimate the percentage of concurrent downstream stormflow constituent load that is from the road crossing relative to the other impervious areas (table 28). For example, there is little development upstream from the Mill Creek at Boedigheimer Road site (table 5), so the modeled contribution from the highway catchment at that site typically accounts for 30.1 percent of the annual concurrent downstream stormflow TCu load (table 28). Farther downstream at the Mill Creek at Mission Street site, the developed area contributions to Mill Creek have increased substantially, and the modeled contribution of the catchment from the Mission Street crossing only accounts for 0.01 percent of the annual concurrent downstream stormflow TCu load.

## Simulation Scenario Overview

Simulation Scenario 2 can be used for different aspects of planning and management. One planning application is to evaluate where to implement BMPs. If the management goal is to reduce the amount of a specific constituent entering a watershed by as much as possible, the median annual reduction (table 27) would inform that decision. For example, if the goal is to reduce sediment using a highway-area BMP in the Mill Creek watershed by as much as possible, implementation of a BMP at the I-5 crossing would provide the most benefit by reducing the median annual suspended sediment load (SSL) by 9,790 lb/yr (not shown). In this simplified scenario, highway-runoff constituent EMCs are considered independent of average daily traffic use for the highway, and the cost of the BMP is not considered, so a more thorough analysis might yield a different prescription.

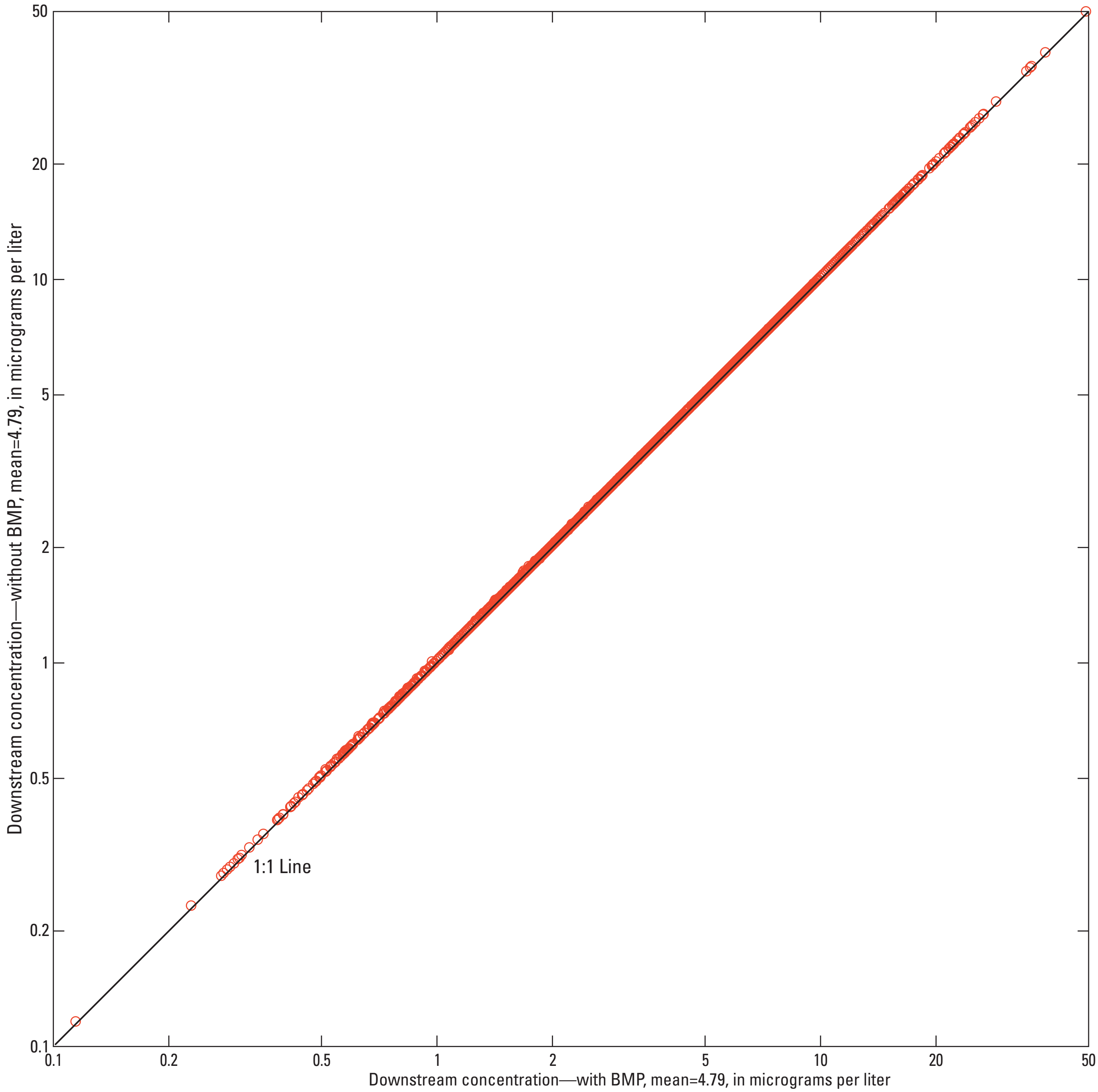



**Figure 45.** Downstream concentrations of total copper with and without best management practices (BMP) implementation for Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway) at Mission Street crossing of Mill Creek, Oregon.

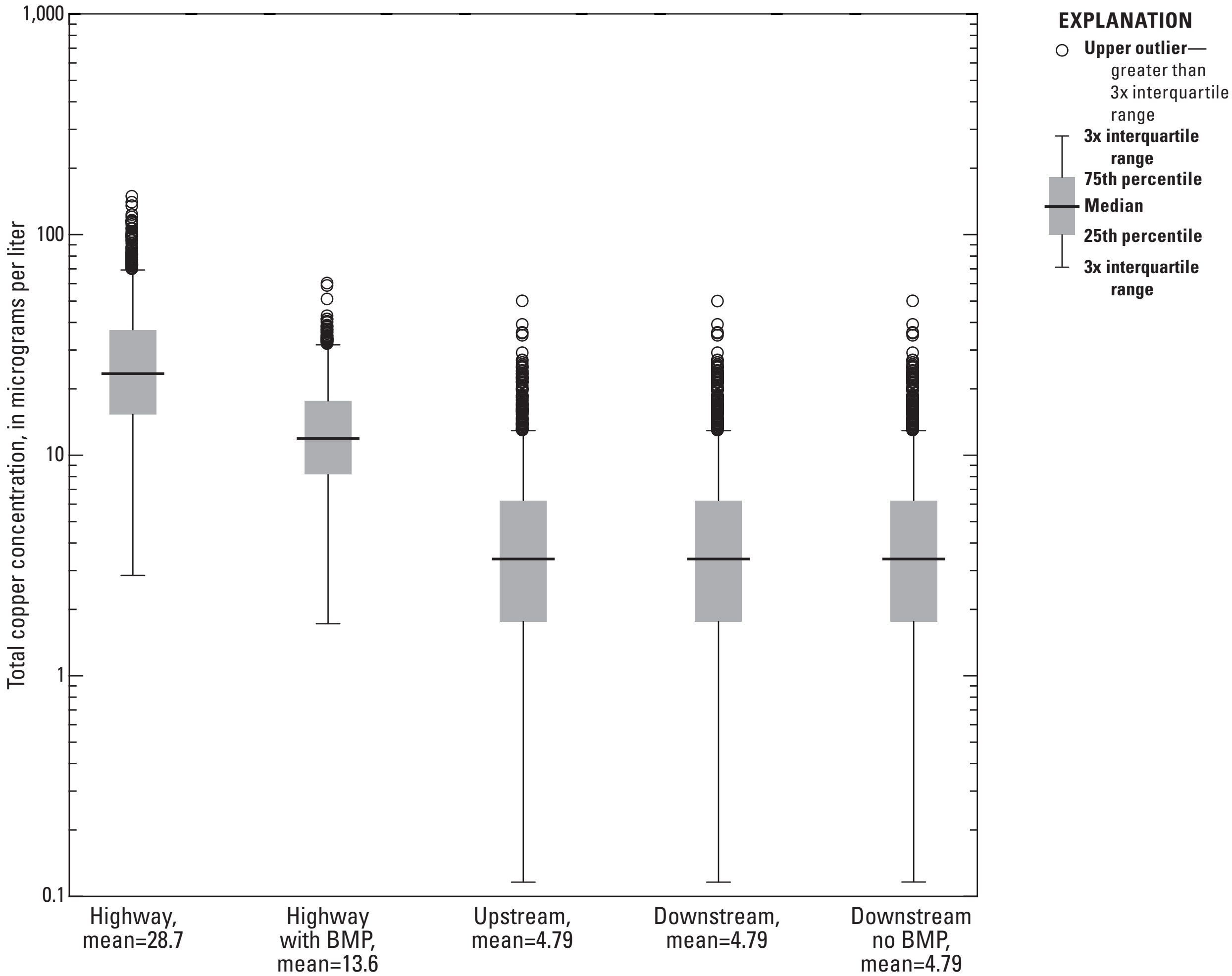



**Figure 46.** Upstream, and downstream concentrations of total copper with and without best management practices (BMP) implementation for Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway) at Mission Street crossing of Mill Creek, Oregon. Mean values in micrograms per liter.

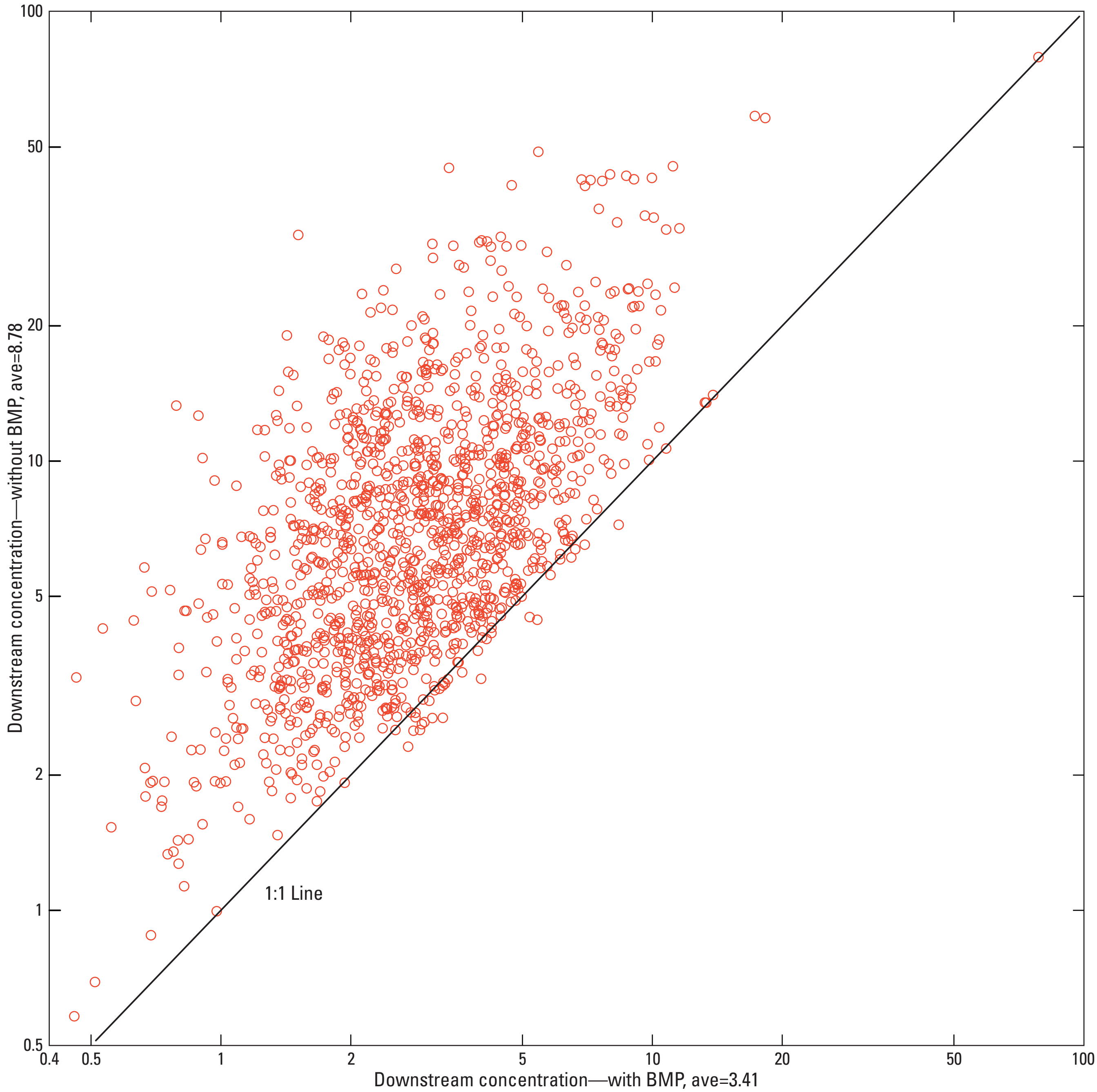



**Figure 47.** Downstream concentrations of total copper in micrograms per liter with and without best management practices (BMP) implementation for Simulation Scenario 2A—Current Conditions (developed area + undeveloped area) at Hamilton Creek, Oregon.

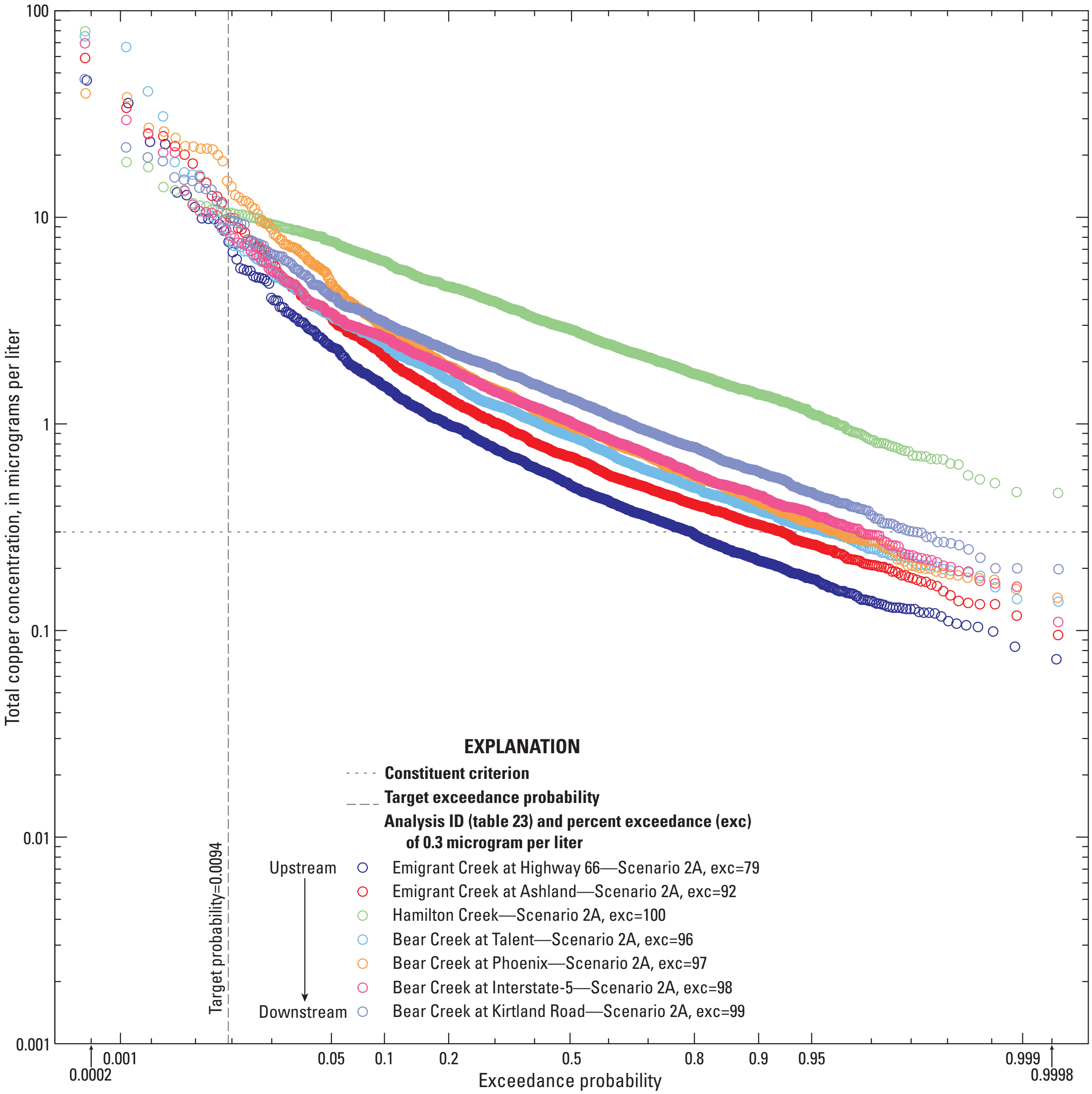



**Figure 48.** Downstream exceedance probabilities of total copper under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area), with best management practices (BMP) implemented, at Bear Creek sites.

**Table 26.** Downstream median annual developed area loading for Simulation Scenario 2A—Current Conditions (developed area + undeveloped area) in Bear and Mill Creek watersheds, Oregon.

[**Abbreviations:** BMP, best management practices; lb, pound; SSL, suspended sediment load; TCu, total copper; TP, total phosophorus; %, percent]

| Site | SSL | | | TCu | | | TP | | | Impervious area (acres) |
|---|---|---|---|---|---|---|---|---|---|---|
| | No BMP (lb) | BMP (lb) | Reduction (%) | No BMP (lb) | BMP (lb) | Reduction (%) | No BMP (lb) | BMP (lb) | Reduction | |
| Bear Creek watershed | | | | | | | | | | |
| Emigrant Creek at Highway 66 | 54,000 | 8,370 | 85 | 6.53 | 2.1 | 68 | 197 | 91.7 | 53% | 153 |
| Emigrant Creek at Ashland | 294,000 | 45,200 | 85 | 39.4 | 12.4 | 69 | 1,140 | 499 | 56% | 866 |
| Hamilton Creek | 31,900 | 4,910 | 85 | 4.05 | 1.37 | 66 | 120 | 55 | 54% | 100 |
| Bear Creek at Talent | 771,000 | 121,000 | 84 | 106 | 31.7 | 70 | 2,820 | 1,320 | 53% | 2,306 |
| Bear Creek at Phoenix | 1,060,000 | 170,000 | 84 | 139 | 43.8 | 68 | 4,245 | 1,955 | 54% | 3,371 |
| Bear Creek at Interstate-5 | 1,620,000 | 253,000 | 84 | 208 | 63.4 | 70 | 6,340 | 2,870 | 55% | 5,196 |
| Bear Creek at Kirtland Road | 3,930,000 | 556,000 | 86 | 509 | 156 | 69 | 14,550 | 6,515 | 55% | 11,236 |
| Mill Creek watershed | | | | | | | | | | |
| Mill Creek at Boedigheimer Road | 11,300 | 1,660 | 85 | 1.34 | 0.423 | 68 | 41.2 | 18.4 | 55% | 12 |
| Mill Creek at Stayton | 29,400 | 4,270 | 85 | 3.77 | 1.13 | 70 | 106 | 50.6 | 52% | 32 |
| Mill Creek at Aumsville | 944,000 | 133,000 | 86 | 115 | 37.1 | 68 | 3,600 | 1,610 | 55% | 1,033 |
| Mill Creek at Mill Creek Road | 1,770,000 | 249,000 | 86 | 217 | 69.8 | 68 | 6,760 | 3,020 | 55% | 1,950 |
| Mill Creek at Turner | 1,980,000 | 289,000 | 85 | 234 | 73.7 | 69 | 7,180 | 3,220 | 55% | 2,118 |
| Mill Creek at Interstate-5 | 3,890,000 | 538,000 | 86 | 435 | 147 | 66 | 13,800 | 6,260 | 55% | 4,170 |
| Mill Creek at Mission Street | 5,460,000 | 754,000 | 86 | 610 | 206 | 66 | 19,400 | 8,780 | 55% | 5,866 |

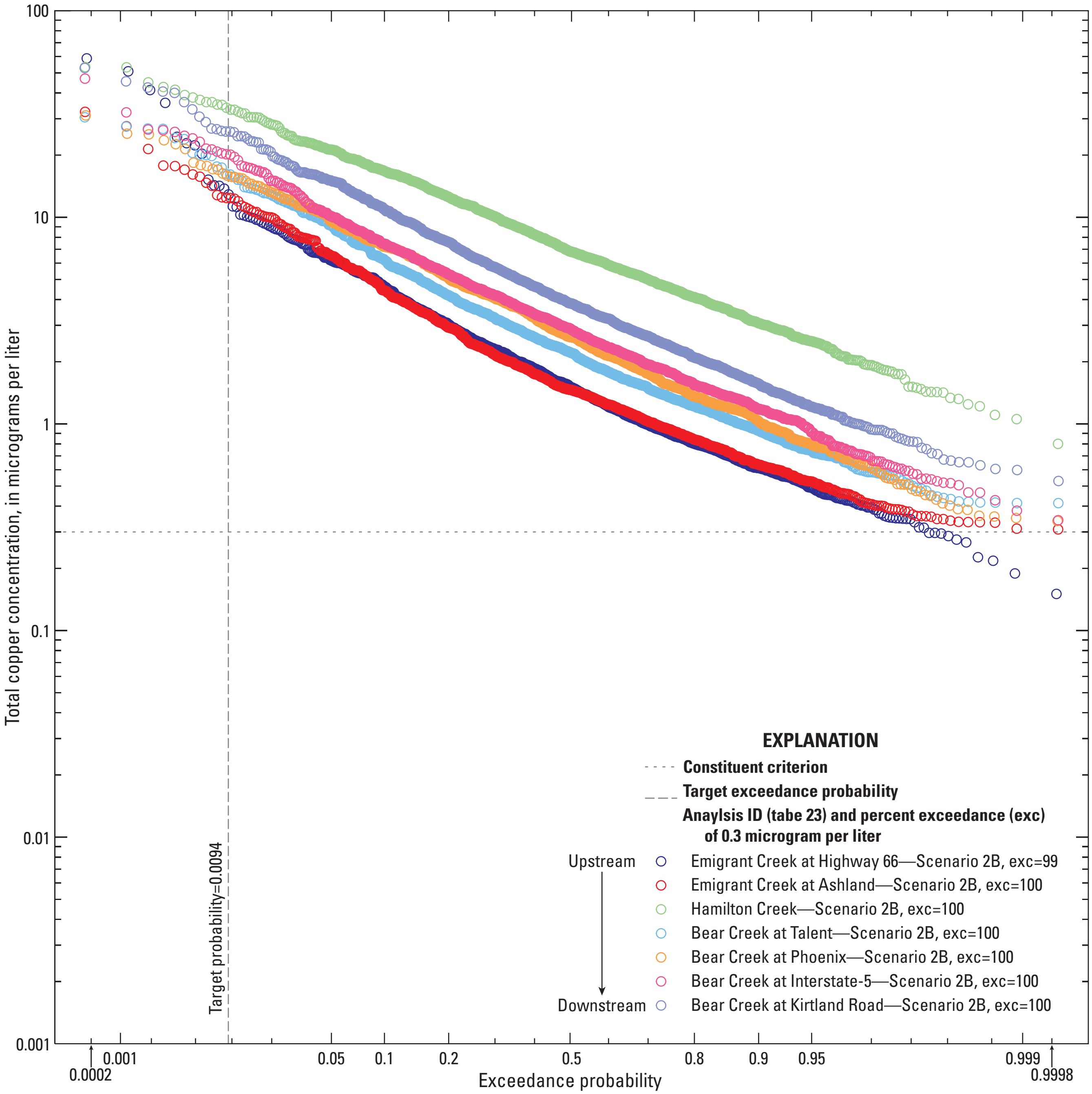



**Figure 49.** Downstream exceedance probabilities of total copper under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with no best management practices (BMP) implemented, at Bear Creek sites, Oregon.

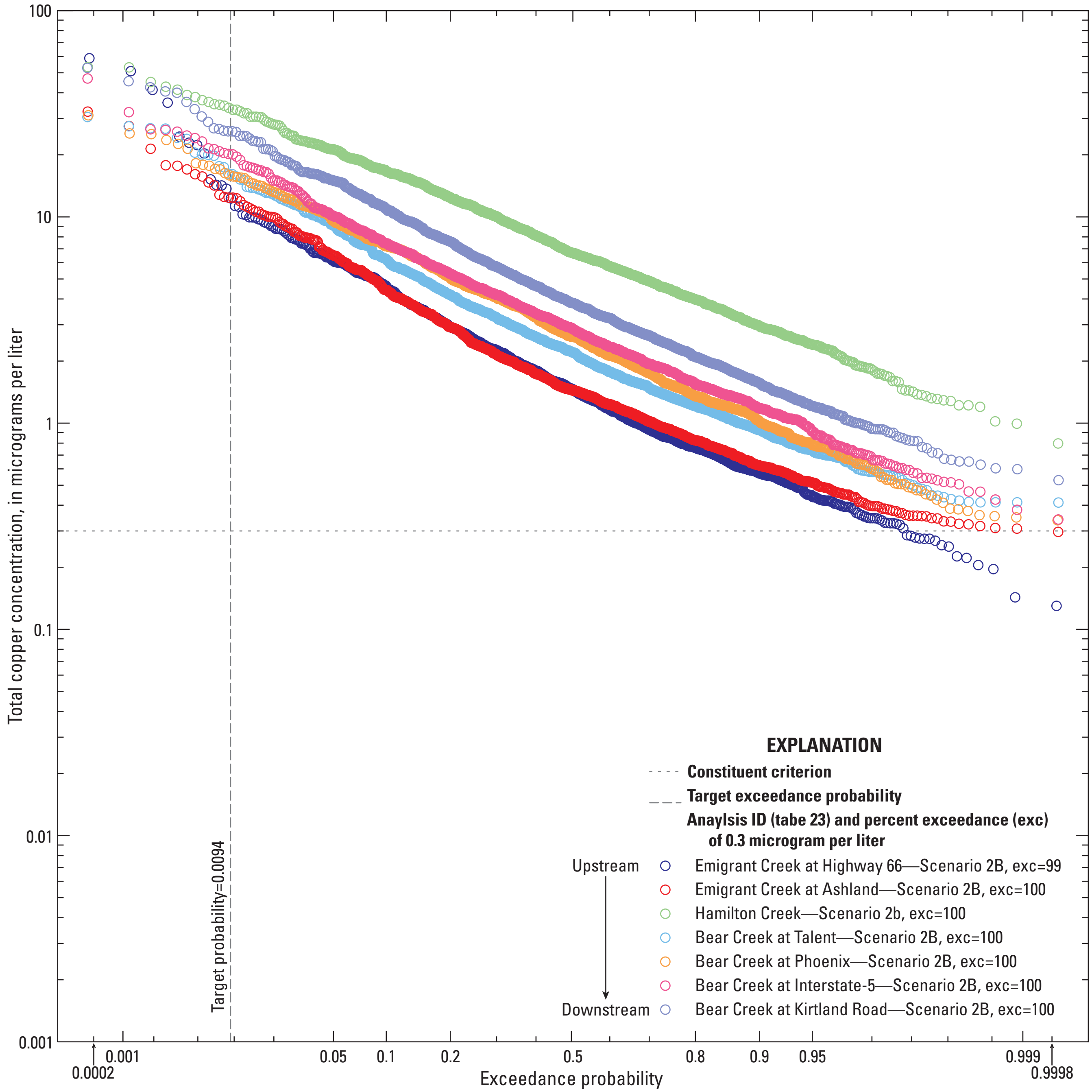



**Figure 50.** Downstream exceedance probabilities of total copper under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with best management practices (BMP) implemented, at Bear Creek sites, Oregon.

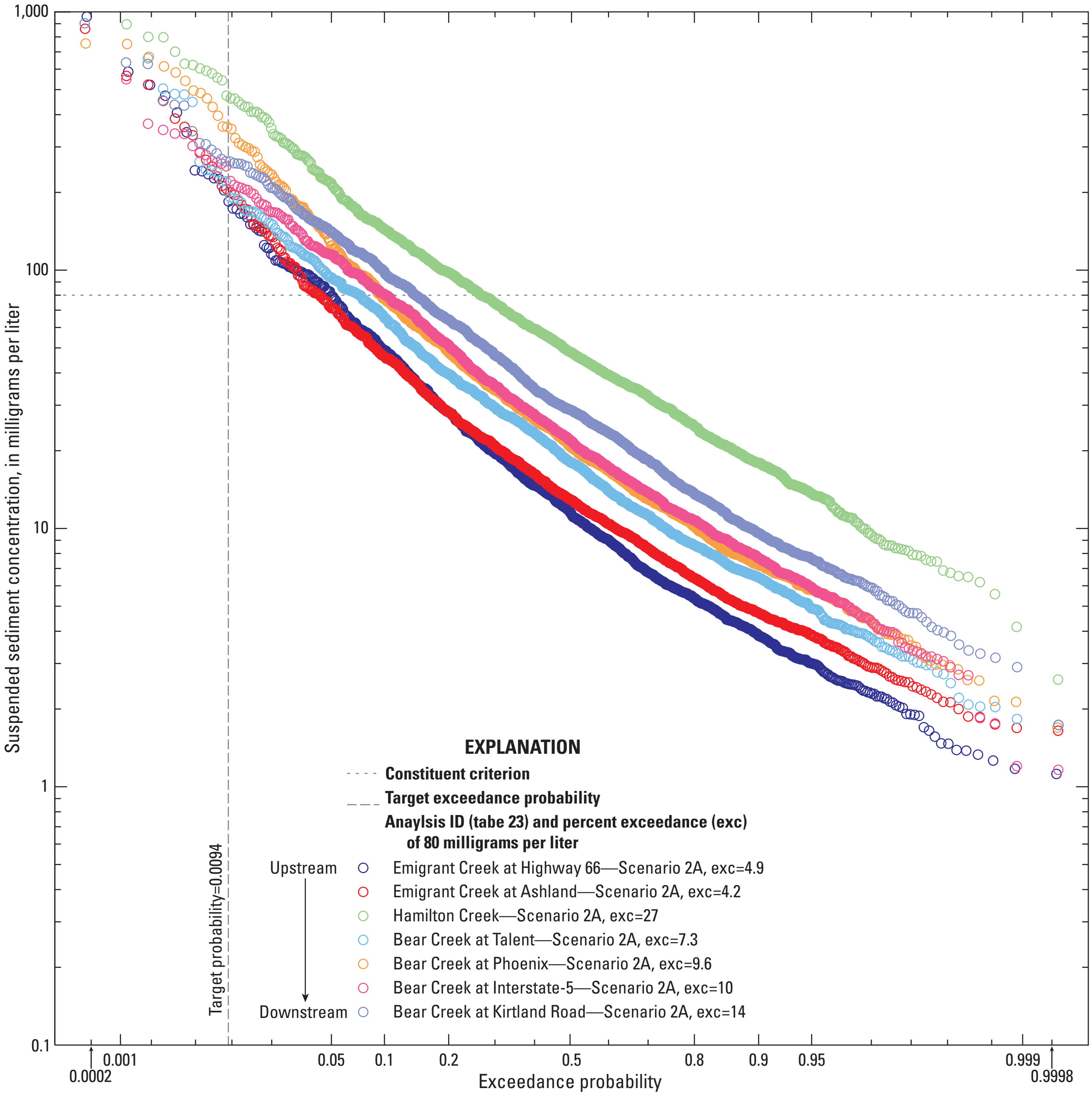



**Figure 51.** Downstream exceedance probabilities of suspended sediment under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area), with no best management practices (BMP) implemented, at Bear Creek sites, Oregon.

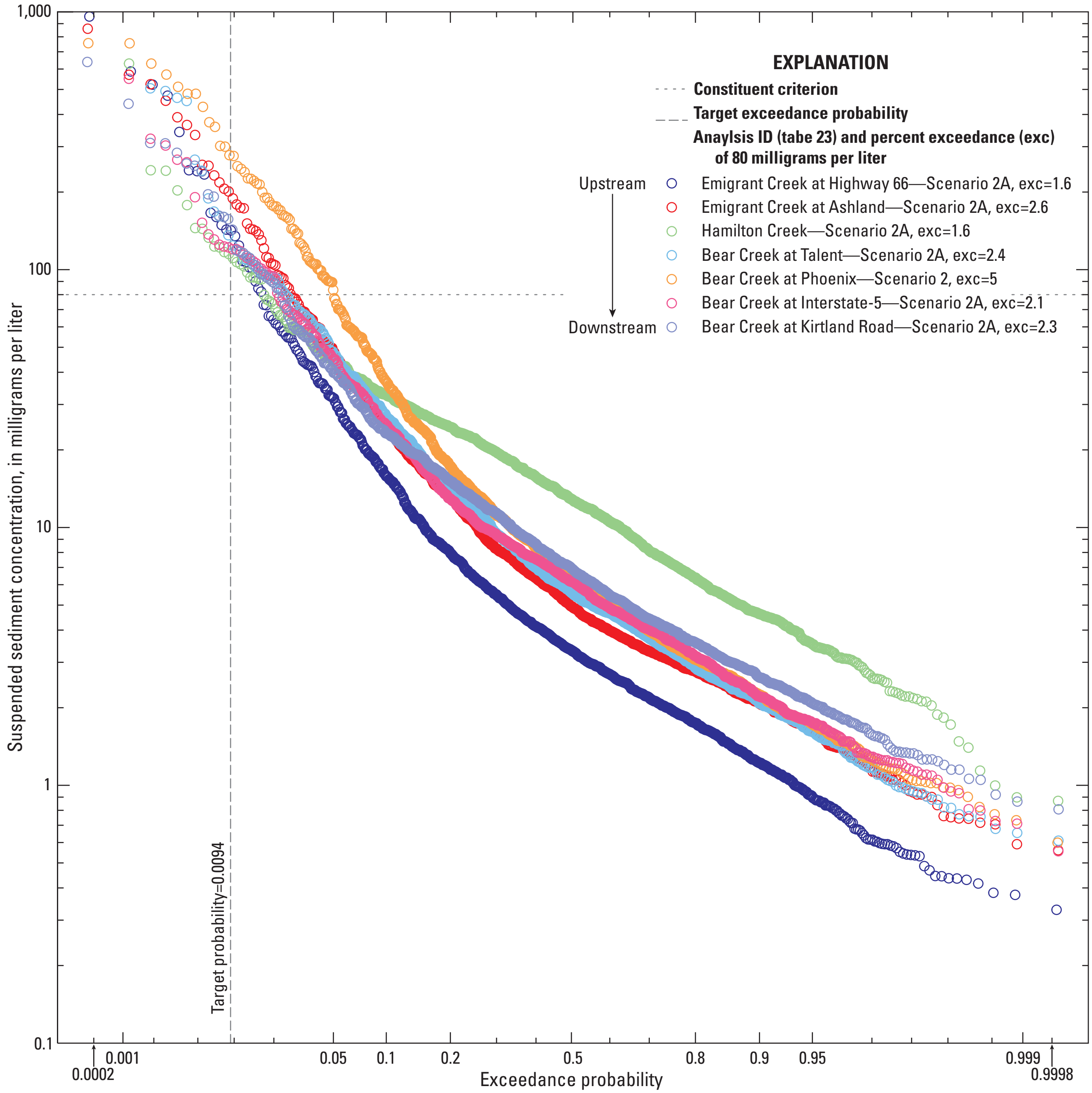



**Figure 52.** Downstream exceedance probabilities of suspended sediment under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area), with best management practices (BMP) implemented, at Bear Creek sites, Oregon.

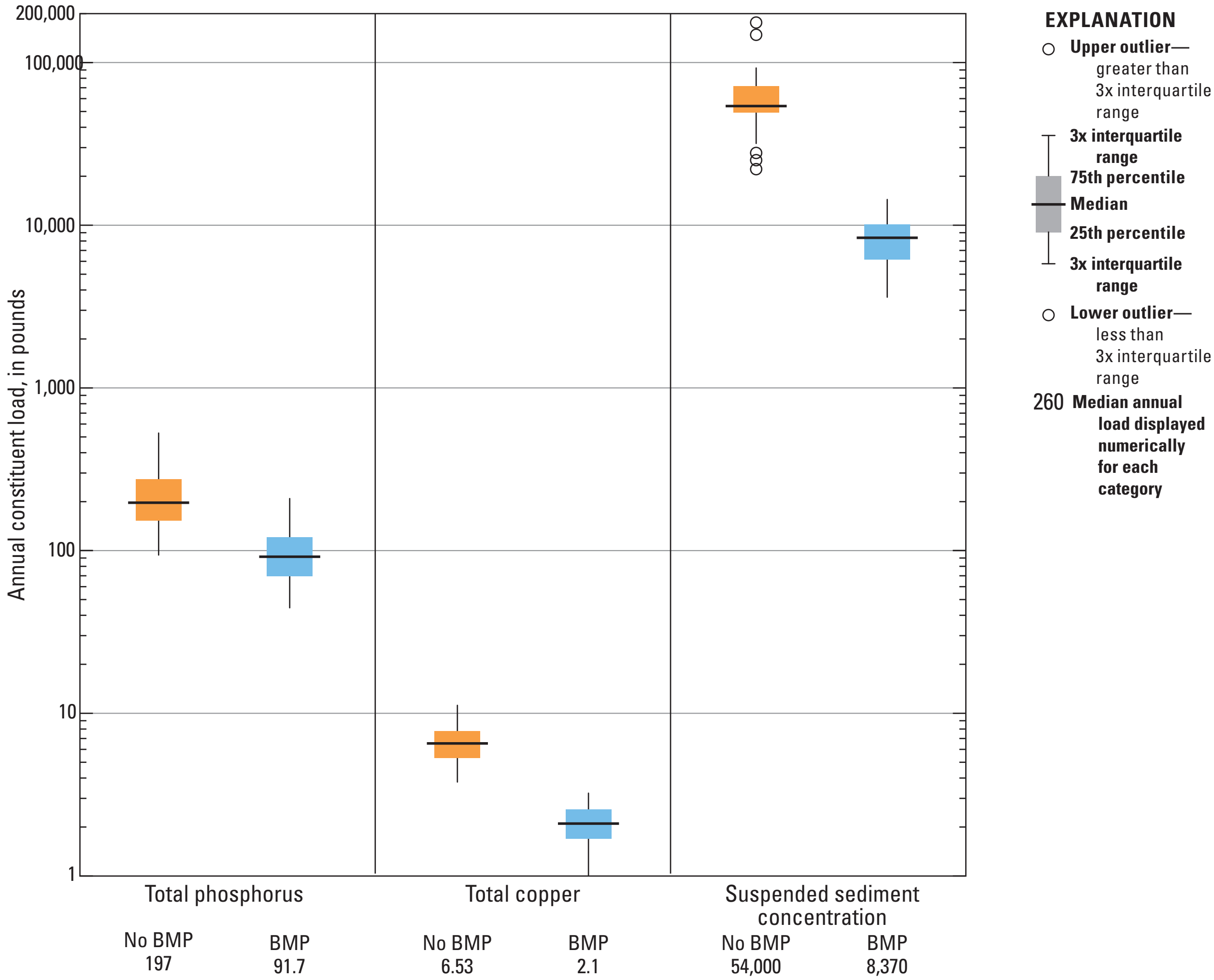



**Figure 53.** Annual developed area loads of total phosphorus, total copper, and suspended sediment with and without best management practice (BMP) implementation under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area) at Emigrant Creek at Highway 66 site, Bear Creek watershed, Oregon.

**Table 27.** Downstream median annual highway loading for Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway) in Bear and Mill Creek watersheds, Oregon.

[**Abbreviations:** BMP, best management practices; lb, pound; SSL, suspended-sediment load; TCu, total copper; TP, total phosophorus; % percent]

| Site | SSL | | | TCu | | | TP | | | Impervious area (acres) |
|---|---|---|---|---|---|---|---|---|---|---|
| | No BMP (lb) | BMP (lb) | Reduction (%) | No BMP (lb) | BMP (lb) | Reduction | No BMP (lb) | BMP (lb) | Reduction (%) | |
| Bear Creek watershed | | | | | | | | | | |
| Emigrant Creek at Highway 66 | 2,090 | 260 | 88 | 0.317 | 0.107 | 66 | 4.06 | 2.01 | 50 | 3.33 |
| Emigrant Creek at Ashland | 1,600 | 224 | 86 | 0.310 | 0.103 | 67 | 3.69 | 1.83 | 50 | 4.52 |
| Hamilton Creek | 228 | 32.2 | 86 | 0.042 | 0.014 | 68 | 0.524 | 0.256 | 51 | 0.7 |
| Bear Creek at Talent | 1,070 | 158 | 85 | 0.213 | 0.061 | 71 | 2.32 | 1.15 | 50 | 1.98 |
| Bear Creek at Phoenix | 1,880 | 279 | 85 | 0.355 | 0.107 | 70 | 4.42 | 2.24 | 49 | 5.58 |
| Bear Creek at Interstate-5 | 49.9 | 7.34 | 85 | 0.009 | 0.003 | 68 | 0.118 | 0.056 | 53 | 0.1 |
| Bear Creek at Kirtland Road | 104 | 12.8 | 88 | 0.018 | 0.006 | 69 | 0.222 | 0.105 | 53 | 0.2 |
| Mill Creek watershed | | | | | | | | | | |
| Mill Creek at Boedigheimer Road | 3,460 | 466 | 87 | 0.577 | 0.183 | 68 | 7.53 | 3.41 | 55 | 2.26 |
| Mill Creek at Stayton | 7,110 | 989 | 86 | 1.25 | 0.387 | 69 | 16.5 | 7.58 | 54 | 4.79 |
| Mill Creek at Aumsville | 890 | 107 | 88 | 0.141 | 0.045 | 68 | 1.85 | 0.87 | 53 | 0.55 |
| Mill Creek at Mill Creek Road | 1,070 | 128 | 88 | 0.169 | 0.055 | 67 | 2.22 | 1.01 | 55 | 0.79 |
| Mill Creek at Turner | 1,370 | 182 | 87 | 0.225 | 0.073 | 68 | 2.99 | 1.40 | 53 | 0.91 |
| Mill Creek at Interstate-5 | 11,100 | 1,310 | 88 | 1.75 | 0.557 | 68 | 22.4 | 10.0 | 55 | 6.93 |
| Mill Creek at Mission Street | 276 | 34 | 88 | 0.045 | 0.015 | 67 | 0.59 | 0.27 | 54 | 0.2 |

**Table 28.** Median annual percentage of constituent load from developed area sourced from site crossing for Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway) in Bear and Mill Creek watersheds, Oregon.

[All values are the percentage contribution of the total load (in pounds) for each constituent at that site. **Abbreviations:** SSL, suspended sediment load; TCu, total copper; TP, total phosophorus]

| Site | SSL | TCu | TP |
|---|---|---|---|
| Bear Creek watershed | | | |
| Emigrant Creek at Highway 66 | 3.73 | 4.63 | 2.02 |
| Emigrant Creek at Ashland | 0.54 | 0.78 | 0.32 |
| Hamilton Creek | 0.71 | 1.03 | 0.43 |
| Bear Creek at Talent | 0.14 | 0.20 | 0.08 |
| Bear Creek at Phoenix | 0.18 | 0.26 | 0.10 |
| Bear Creek at Interstate-5 | 0.00 | 0.00 | 0.00 |
| Bear Creek at Kirtland Road | 0.00 | 0.00 | 0.00 |
| Mill Creek watershed | | | |
| Mill Creek at Boedigheimer Road | 23.4 | 30.1 | 15.5 |
| Mill Creek at Stayton | 19.5 | 24.9 | 13.5 |
| Mill Creek at Aumsville | 0.09 | 0.12 | 0.05 |
| Mill Creek at Mill Creek Road | 0.06 | 0.08 | 0.03 |
| Mill Creek at Turner | 0.07 | 0.10 | 0.04 |
| Mill Creek at Interstate-5 | 0.28 | 0.40 | 0.16 |
| Mill Creek at Mission Street | 0.01 | 0.01 | 0.00 |

Another potential management goal may be to maximize the environmental benefit by optimizing the reduction in the number of constituent exceedances within the number of river miles that are affected by BMP implementation. Returning to the previous example with this specific goal, model results indicate the best place to implement a BMP in the Mill Creek watershed would be at the Boedigheimer Road crossing. Even with BMP implementation here, the probability of SSC standard exceedances is still around 1 percent (fig. 54), which is higher than the 0.66 percent needed to have a 3-year recurrence interval for exceedances. However, the rate of exceedance would be lowest at this site if a BMP was implemented. Therefore, if a BMP is implemented at this site, it would maximize the reduction in the number exceedances and river miles that are within the targeted water-quality criterion.

A third management goal might be to assess the cost of implementing BMPs for a developed area. Following the previous example of reducing sediment, the most upstream site in the Mill Creek watershed that can achieve the SSC water-quality criterion by implementing BMPs in all upstream developed areas is the Aumsville crossing (fig. 55). Implementing BMPs for the noncontiguous 1,033 acres (1.61 $mi^2$; table 5) of impervious area upstream from the Aumsville crossing may be prohibitively expensive. However, the probability of exceeding the SSC criterion if all 1.61 $mi^2$ were treated with BMPs would be 0.36 percent, which is less than the target value of 0.66 percent. If the water-quality criteria are achievable by using BMPs, then decision makers can use SELDM to estimate the minimum treatment area that is needed to meet the water-quality criterion.

To this end, additional simulations at Aumsville were developed in which various percentages of upstream impervious areas had BMPs implemented (25-, 50-, and 75-percent). Results indicate that a BMP implementation rate of about 25 percent of all upstream impervious area would nearly achieve the target rate of SSC criterion exceedance (0.72 percent). In this specific example, BMP implementation of around 0.4 $mi^2$ of impervious area would result in meeting SSC target goals.

## Simulation Scenario 3—Alternative Road Layouts

Simulation Scenario 3 was designed to evaluate the sensitivity of SELDM to various road layouts. One site was selected, and the highway site characteristics (highway catchment drainage area, drainage length, mean basin slope, impervious fraction, and basin development factor) from other locations were superimposed at that site, while all other characteristics were left unchanged. In this manner, managers may evaluate the effects of different potential roadway conditions.

The Mill Creek at Turner site was selected for Simulation Scenario 3 because it represents approximately median levels of upstream drainage area, highway conditions, and precipitation conditions for the Mill Creek watershed. Highway site characteristics from the Mission Street, I-5, Mill Creek Road, Aumsville, Stayton, and Boedigheimer Road sites were superimposed on the Turner site, while all other scenario variables were left unchanged from the Turner site. This allowed for direct comparison of the various highway configurations and the resulting downstream EMCs and loading. Upstream was assumed to be undeveloped for this scenario, because the effect of the road conditions will be more easily evident if upstream conditions have lower concentrations of constituents (higher concurrent upstream stormflow constituent loads tend to drown out other effects). BMP implementation was not evaluated for this simulation scenario.

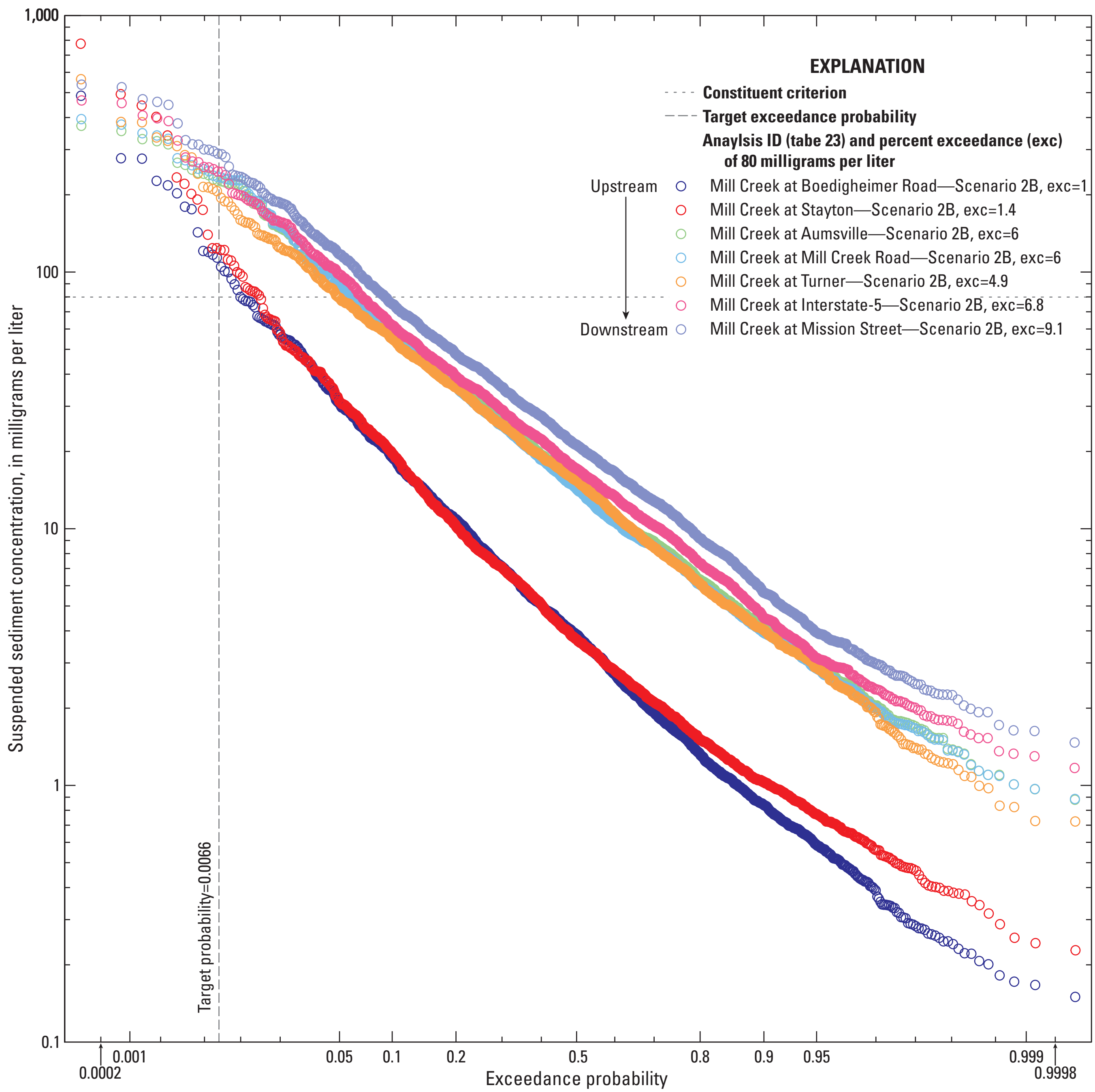



**Figure 54.** Downstream exceedance probabilities of suspended sediment concentration under Simulation Scenario 2B—Current Conditions (developed area + undeveloped area + highway), with best management practice (BMP) implemented, at Mill Creek sites, Oregon.

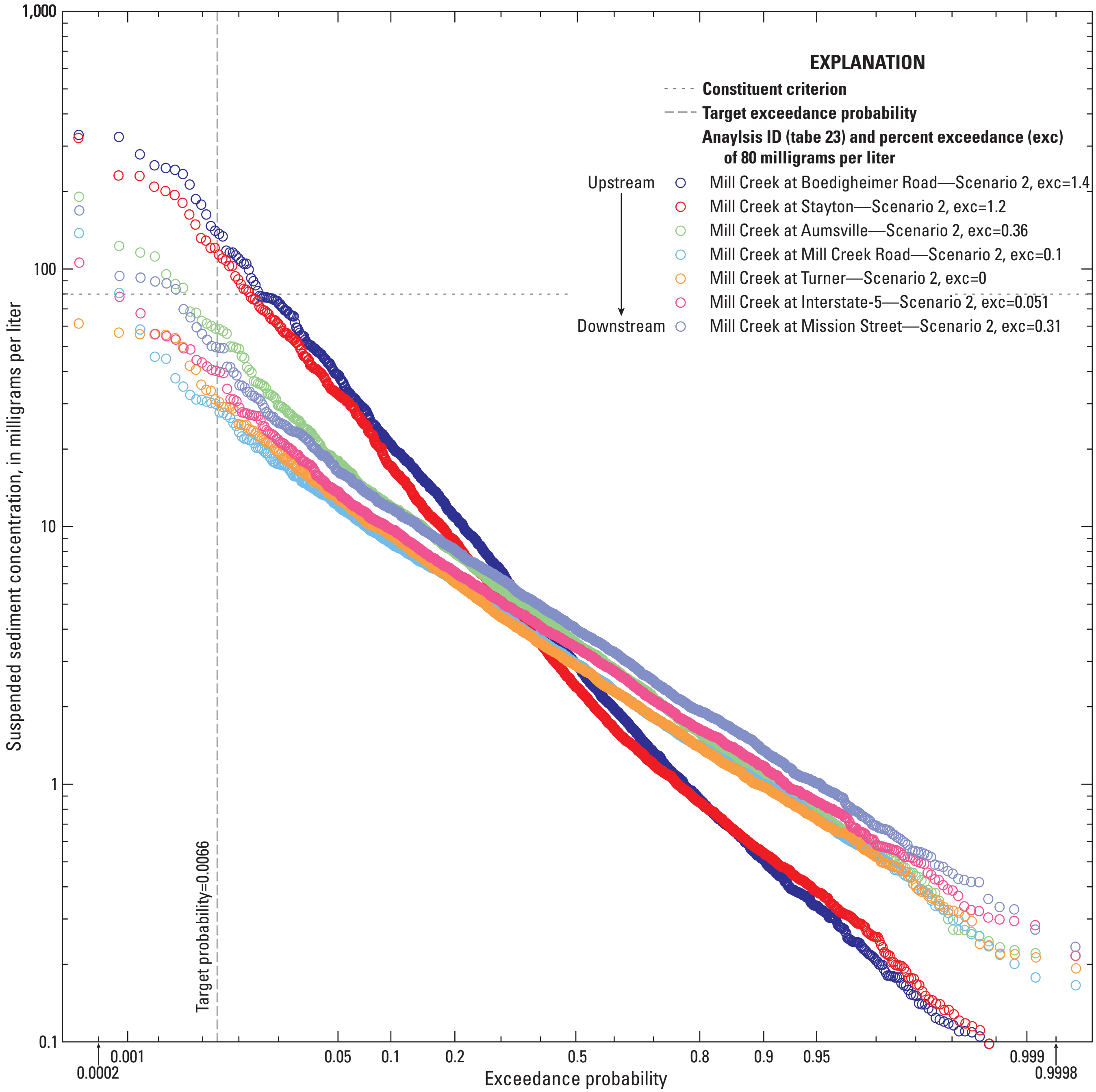



**Figure 55.** Downstream exceedance probabilities of suspended sediment concentration under Simulation Scenario 2A—Current Conditions (developed area + undeveloped area), with best management practice (BMP) implemented at Mill Creek sites, Oregon.

## Runoff-Quality Risk Analysis

Highway site characteristics appear to have a low to moderate effect on modeled water-quality criterion exceedance probabilities. For TCu, the exceedance probabilities calculated for Mill Creek sites, assuming no BMP implementation, ranged from 19 to 28 percent (fig. 56). As would be expected, the highest modeled rate of exceedance was the I-5 highway configuration, which had the largest highway catchment drainage area. Conversely, the lowest modeled exceedance probabilities (the Mission Street and Aumsville sites) were the roadway configurations with the smallest highway catchment drainage areas (table 5).

Even less variance is evident in modeled TP and SSC EMCs. For example, the modeled rates of TP EMC exceedances are very low (less than 0.2 percent) at all highway configurations (fig. 57), indicating that, within the range tested, the roadway configuration would have little effect on the rate of TP criterion exceedance probability (SSC results not shown).

## Runoff-Quality Annual Load Analyses

Although the exceedance probabilities and constituent EMCs of concurrent downstream stormflow did not appear to be sensitive to the road configuration, annual loading from the highway does display more variability and is related to highway drainage area (table 29). For example, model results indicate using the road configuration from I-5 produces about 8 times as much SSL as the existing road configuration at Turner. Conversely, adopting the road configuration at Mission Street produces about one-fifth of the SSL as the existing road configuration at Turner. The other water-quality constituents had similar patterns (table 29).

## Simulation Scenario Overview

Simulation Scenario 3 indicates that while the road configuration may not have a large effect on constituent EMCs of concurrent downstream stormflow or probabilities of exceeding water-quality criteria, road configuration can have a large effect on constituent loading at the crossing. Road configurations with large highway catchment drainage areas such as the I-5 configuration result in more constituent loading into the stream. Conversely, configurations with small highway catchment drainage areas can produce dramatically lower levels of constituent loading. These results indicate that different configurations could be considered to minimize constituent loading, or to balance constituent loading against other considerations such as expected levels of traffic congestion. Although the total road width may be determined by required traffic capacity, reduction in contributing highway catchment drainage area by allowing highway runoff to infiltrate into the ground (disconnection of approaches), rather than flowing from the stormwater infrastructure into the creek (use of trunk-line storm sewer systems), may be used to achieve some reduction in contributing area. In addition, alternative alignments and other choices may reduce the amount of impervious surface that drains into a stream.

# Simulation Scenario 4—Varying Road Width

Simulation Scenario 4 was designed to evaluate the sensitivity of SELDM to road width, which was used to vary the drainage area. This scenario is similar to Simulation Scenario 3, but instead of focusing on all highway site characteristics (area, drainage length, drainage slope, and basin development factor) this scenario focuses on only one, road width. Seven different road widths were modeled, ranging from 16 to 112 ft in 16-ft increments. All other variables were left unchanged, including the location (Mill Creek at Turner).

## Runoff-Quality Risk Analysis

The cumulative distribution functions of all seven road width scenarios (not pictured) are nearly identical. For example, the modeled probability of exceeding the TCu water-quality criterion for a given storm ranges from 18 percent (16 ft of road width) to 19 percent (112 ft of road width). Results for the other constituents are similar, suggesting the road width at this location has little effect on constituent EMC exceedance probabilities.

## Runoff-Quality Annual Load Analyses

Similar to Simulation Scenario 3, the median annual constituent loading from highway contributions varied widely (table 30) and are directly proportional to road width in this scenario. For example, doubling the road width from 16 to 32 ft effectively doubled the median annual TP load from highway discharge from 0.74 to 1.5 lb/yr.

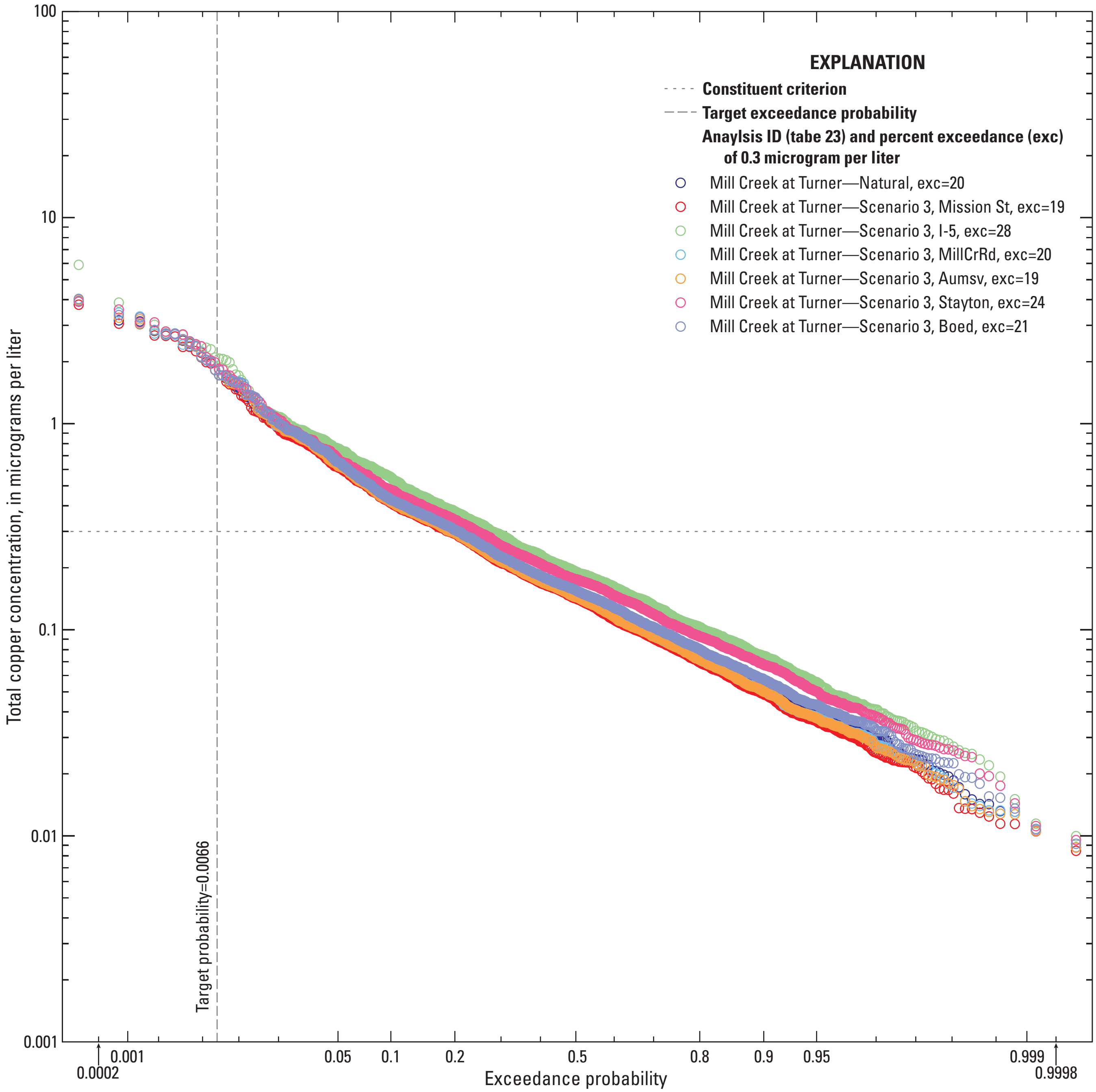



**Figure 56.** Downstream exceedance probabilities of total copper concentration under Simulation Scenario 3—Alternative Road Layouts, with no best management practice (BMP) implemented at Mill Creek sites, Oregon.

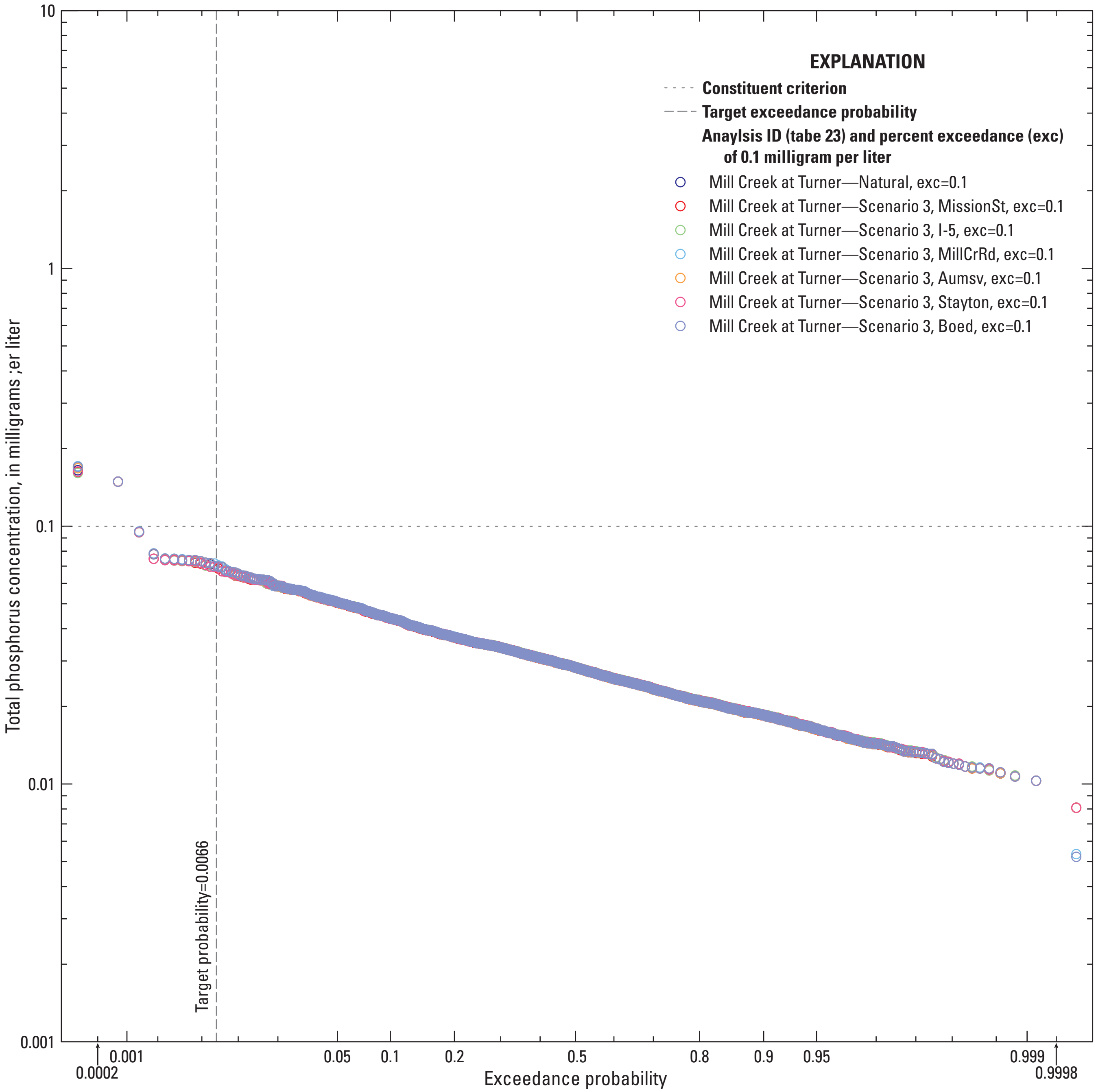



**Figure 57.** Downstream exceedance probabilities of total phosphorus concentration under Simulation Scenario 3—Alternative Road Layouts, with no best management practice (BMP) implemented, at Mill Creek sites, Oregon.

**Table 29.** Median annual highway loading for Simulation Scenario 3—Alternative Road Layouts, for Mill Creek at Turner, Oregon.

[**Abbreviations:** lb, pound; SSL, suspended sediment load; TCu, total copper; TP, total phosophorus; DA, drainage area]

| Road configuration | SSL (lb) | TCu (lb) | TP (lb) | Highway DA (acres) |
|---|---|---|---|---|
| Mill Creek at Boedigheimer Road | 3,410 | 0.57 | 7.4 | 2.26 |
| Mill Creek at Stayton | 7,230 | 1.22 | 16 | 4.79 |
| Mill Creek at Aumsville | 831 | 0.14 | 1.8 | 0.55 |
| Mill Creek at Mill Creek Road | 1,020 | 0.17 | 2.2 | 0.79 |
| Mill Creek at Turner | 1,370 | 0.23 | 3.0 | 0.91 |
| Mill Creek at Interstate-5 | 10,500 | 1.76 | 23 | 6.93 |
| Mill Creek at Mission Street | 273 | 0.05 | 0.58 | 0.2 |

**Table 30.** Median annual highway loading for Simulation Scenario 4—Varying Road Width, for Mill Creek at Turner, Oregon.

[**Abbreviations**: ft, feet; lb, pound; SSL, suspended sediment load; TCu, total copper; TP, total phosophorus; DA, Drainage area]

| Road width (ft) | SSL (lb) | TCu (lb) | TP (lb) | Highway DA (acres) |
|---|---|---|---|---|
| 16 | 342 | 0.06 | 0.74 | 0.226 |
| 32 | 684 | 0.12 | 1.5 | 0.453 |
| 48 | 1,030 | 0.17 | 2.2 | 0.679 |
| 64 | 1,370 | 0.23 | 2.9 | 0.906 |
| 80 | 1710 | 0.29 | 3.7 | 1.132 |
| 96 | 2,050 | 0.35 | 4.4 | 1.358 |
| 112 | 2,390 | 0.40 | 5.2 | 1.585 |

## Simulation Scenario Overview

Simulation Scenario 4 shows the importance of road width (and by association, highway catchment drainage area) to annual constituent loading. In this simplified scenario, constituent loading from the highway is directly proportional to the road width at the crossing. A more detailed analysis might yield different results. For example, doubling the road width from 12 to 24 ft (by doubling the number of lanes) may not also double the daily vehicular traffic at the crossing. If these constituents are, exclusively, a function of annual average daily traffic (AADT) (table 16) rather than the effect of background developed-area emissions associated with larger AADTs, then the additional roadway area may not produce a proportionally larger load. If background emissions and therefore roadway deposition are higher, then the additional area, which collects and conveys deposited materials may contribute greater loads per unit area.

This scenario highlights another potential use for SELDM. Individual characteristics can be adjusted to meet or exceed specific targets. For example, if a goal of a new bridge installation was to limit the TP input from the catchment runoff to 2 lb or fewer, the results from this simplified scenario would indicate limiting the road width to 32 ft or fewer.

## Simulation Scenario 5—Changes To Impervious Area

Simulation scenario 5 was designed to evaluate the sensitivity of the amount of upstream impervious area on constituent EMCs of concurrent downstream stormflow. Simulation scenario 5 was developed in a similar manner to scenario 2A, in which all of the runoff simulated from the developed impervious area upstream from the site of interest enters the stream just upstream from the crossing. As with the previous simulations, the developed area runoff is simulated by using the highway module with the urban-runoff statistics (table 17). The upstream water quality was simulated by using the undeveloped-area transport curves (table 21). The amount of area designated as impervious was then varied from 5 to 30 percent in increments of 5 percent (as scenarios 5A–F; table 23). Only the Mill Creek at Turner site was used for these analyses.

### Runoff-Quality Risk Analysis

Model results indicate the probability of exceeding specific water-quality criteria varies based on the percentage of imperviousness upstream. For example, if the area upstream from the Mill Creek at Turner site were 5 percent impervious, the expected probability of exceeding the SSC criterion is 7.4 percent (fig. 58). In contrast, given upstream imperviousness values of 15 and 30 percent, the probabilities of exceeding the same criterion at the same site are 17 and 26 percent, respectively.

TP and TCu constituent EMCs of concurrent downstream stormflow displayed similar levels of variability, which translated into high levels of variability for modeled exceedance probabilities of TP (ranging from 36 to 75 percent). Conversely, TCu levels were high enough that the water-quality criterion was routinely exceeded in all simulations. At 5 percent upstream imperviousness, the TCu criterion was exceeded in 98 percent of modeled storms, and for all other upstream levels of imperviousness, exceedances occurred during over 99.9 percent of modeled storm events (simulation results not shown).

### Runoff-Quality Annual Load Analyses

The median annual constituent load is proportional to the percentage of impervious drainage area upstream from the crossing. For example, doubling the impervious drainage area from 15 to 30 percent for Mill Creek at Turner site results in a doubling of median annual TP urban-runoff load from 37,100 to 74,200 lb (table 31). The median annual loads of the other constituents considered (SSC and TCu) were also proportional to the percentage of impervious upstream drainage area (not shown).

### Simulation Scenario Overview

Simulation scenario 5 was designed to investigate the importance of upstream impervious (developed) drainage area. The results show that concurrent downstream stormflow water-quality constituent levels are highly correlated with the percentage of area upstream that is impervious. For higher percentages of impervious upstream drainage area, more constituent is received, and the constituent EMCs of concurrent downstream stormflow become more correlated with developed area runoff constituent EMCs and less correlated with constituent EMCs of concurrent upstream stormflow (fig. 59). Kendall’s Tau (also known as the Kendall rank correlation coefficient) is a statistical measure of ordinal association between two measured qualities (Kendall, 1938). A Tau value of 1.0 indicates a perfect positive correlation, whereas a Tau value of 0.0 indicates no correlation.

At 5-percent impervious area upstream, the correlation between the concurrent downstream stormflow and the developed area runoff TP EMCs is about the same as the correlation between the concurrent downstream stormflow and the concurrent upstream stormflow TP EMCs. As the percentage of upstream impervious area increases, the correlation between concurrent upstream stormflow and concurrent downstream stormflow TP EMCs starts to decrease slowly, whereas the correlation between concurrent downstream stormflow and highway TP EMCs increases relatively quickly. All of these Kendall’s Tau values are statistically significant at a significance level of 0.01.

Simulation scenario 5 indicates that the percentage of upstream urban area has a marked effect of concurrent downstream stormflow constituent EMCs. In this example, at imperviousness levels greater than 5 percent, the concurrent downstream stormflow TP EMCs become more highly correlated with developed area runoff than with concurrent upstream stormflow. These results can be used to understand the sensitivity of constituent concentrations to urban development (imperviousness). In such instances, an end-user might consider the decision of where to install a bridge or culvert, or construct a BMP implementation based in part on development patterns or future development plans.

## Limitations Of The Analyses

The analyses described in this report were designed to produce planning-level estimates of stormwater flows, concentrations, and loads from undeveloped basins, developed areas, and road crossings to assess relative contributions of different land covers and potential effectiveness of different management measures for meeting hypothetical water-quality criteria in selected basins in Oregon. Planning-level estimates include substantial uncertainties, which commonly are on the scale of one or more orders of magnitude (Granato, 2013). To acquire greater accuracies that could be used for purposes other than planning-level estimates, a level-three analysis with local data collection would be necessary.

Constituent concentration statistics for undeveloped non-highway land were calculated with available regional data, but may not be representative of true runoff concentrations from the watersheds of interest. Although highway-runoff concentration statistics were calculated from Oregon-highway sampling sites, these statistics vary greatly between locations, and the statistics used many not be representative of individual highways. Similarly, the urban-runoff statistics from the 2012 International BMP Database vary greatly and application of these statistics to particular sites in Oregon is uncertain. BMP treatment statistics represent the effects of a generic BMP design (Granato, 2014; Granato and Jones, 2017). In practice, individual BMP designs may be optimized for the hydrology and water quality of the area, and BMP treatment may be more effective if tailored for specific water-quality constituents.

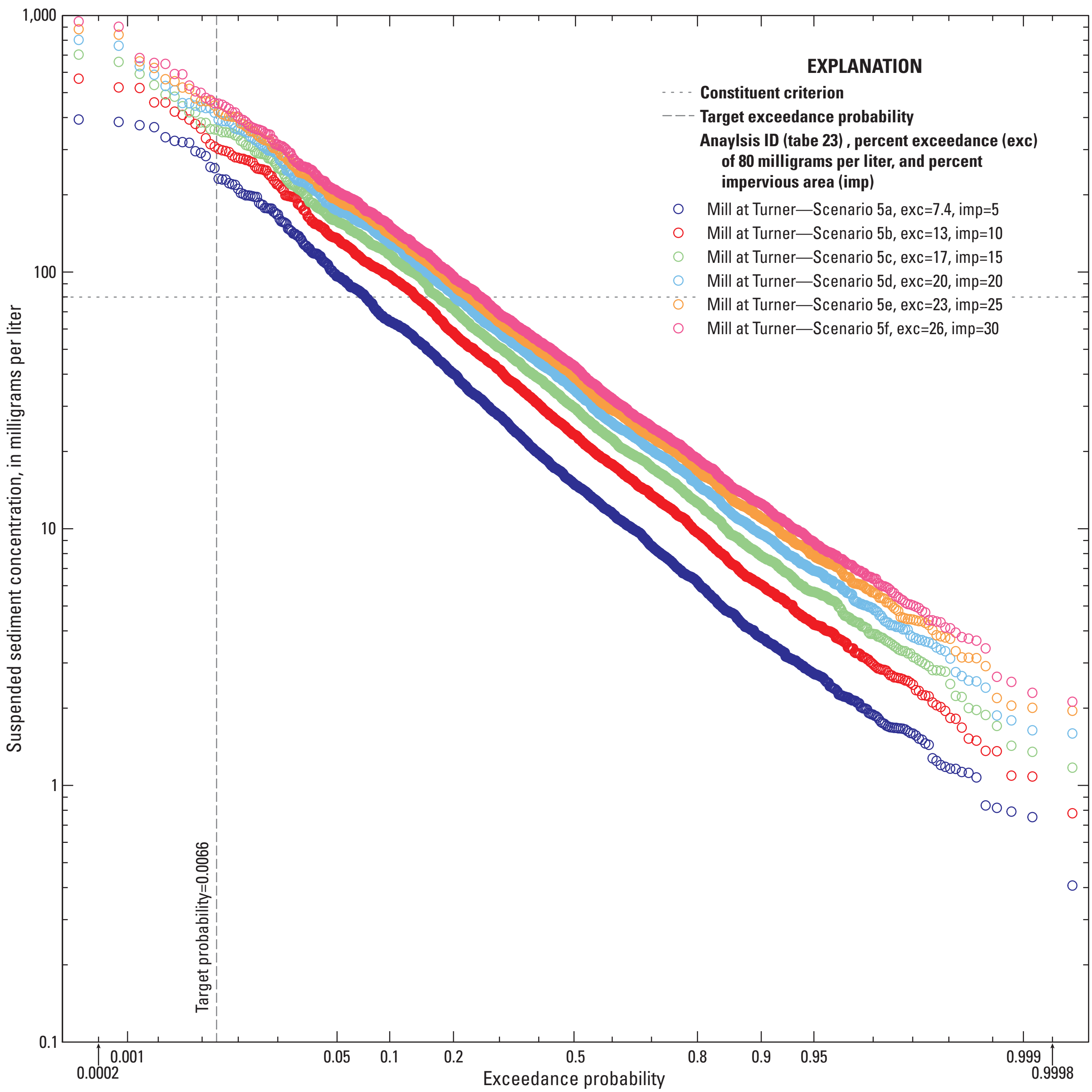



**Figure 58.** Downstream exceedance probabilities of suspended-sediment concentration under Simulation Scenario 5—Changes to Impervious Area, with no best management practice (BMP) implemented, at Mill Creek sites.

**Table 31.** Median annual highway loading for Simulation Scenario 5—Alternative Road Layouts for Mill Creek at Turner, Oregon.

[**Abbreviations:** lb, pound; SSL, suspended sediment load; TCu, total copper; TP, total phosophorus]

| Percentage of upstream area that is impervious | SSL (lb) | TCu (lb) | TP (lb) |
|---|---|---|---|
| 5 | 3,410,000 | 403 | 12,400 |
| 10 | 6,810,000 | 806 | 24,700 |
| 15 | 10,200,000 | 1,210 | 37,100 |
| 20 | 13,600,000 | 1,610 | 49,500 |
| 25 | 17,000,000 | 2,010 | 61,900 |
| 30 | 20,400,000 | 2,420 | 74,200 |

Annual loading from impervious areas that contribute to streams may be overestimated, as roadway or other impervious areas often drain to local land surfaces rather than to the contributing stream network. In addition, loads, yields (loads per unit area), and concentrations discussed in this report are for stormwater runoff only. Loadings from wastewater treatment plants or base-flow loading from fertilizer applications, agricultural underdrains, septic-system effluent, other commercial or industrial sources, or natural geologic sources were not explicitly considered. The transport curves that were developed are from basins with minimal development; although the effects of such sources in these data are expected to be minimal, the effects may not be absent.

SELDM is not calibrated by fitting input values to a historical record; SELDM is calibrated by selecting statistics for runoff-quality variables and BMP-treatment variables from robust and representative datasets (Granato, 2013, 2014; Granato and Jones, 2015, 2016, 2017). In this study, priority was given to data collected in or near Oregon. The input statistics that are selected can have a substantial effect on the potential number of water-quality exceedances in a simulation and the estimated annual loads. Because available water-quality data are used to simulate random long-term populations of concentration data, the representativeness of simulation results depend on the spatial and temporal representativeness of that data. Highway-runoff data are from six highway sites, but there are 73,868 mi of highway (Oregon Department of Transportation, 2017), and tens of thousands of road and other stream crossings in Oregon. Similarly, water-quality data were used from 16 stream monitoring sites, but there are an estimated 300,878 mi of streams with 87,551 mi of perennial streams in the National Hydrography Dataset for Oregon (U.S. Environmental Protection Agency, 2013b). Although professional judgement was used to select statistics, which are representative of water quality in Oregon, additional water-quality data associated with highway runoff, developed area runoff, BMP performance, and receiving water-quality data are needed to estimate the uncertainties in simulated results.

Using the EMC results to evaluate against a CMC may add uncertainty to the analysis. Precipitation events typically last about 10–13 hours (table 7), whereas a CMC is defined for 1 hour. There is a paucity of hourly water-quality data from highway runoff. Further research would be needed to determine the best approach for evaluating a CMC using EMC results.

Individual simulation scenario results are indicative of a specific geographic location, and may have limited application downstream. Estimating effects farther downstream from a road crossing would necessitate an approach in which output from an upstream model is used as input for a downstream model, similar to Simulation Scenario 2. Using this technique, a new simulation scenario could be set up for each road crossing, tributary input, or other location where constituent concentrations may change due to inputs.

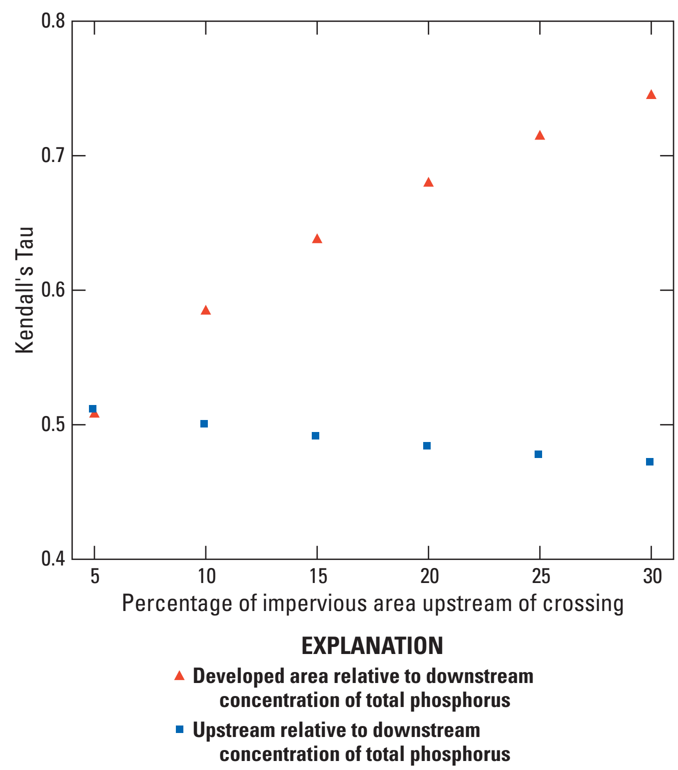



**Figure 59.** Relation between the percent of urban impervious area with Kendall's Tau value of upstream, downstream and developed area suspended sediment concentrations, Simulation Scenario 5— Alternative Road Layouts for Mill Creek at Turner, Oregon.

# Summary

Adverse effects of stormwater on receiving waters represent a substantial water quality issue Nationwide. Managing agencies of impervious surfaces need information about the potential magnitude of their contributions and the potential effectiveness of methods to mitigate the adverse effects of runoff.

Stormwater runoff commonly results in increases in concentrations and loads of water-quality constituents in receiving waters, but mitigation measures require substantial investments to build and maintain structural best management practices (BMPs). Federal and State regulations, in accordance with the Oregon Department of Transportation (ODOT) mission goals, place the responsibility of mitigating potentially adverse effects of runoff from state-owned roadways on ODOT. Because highway corridors are linear systems with limited rights-of-way and road-side access issues, options for the construction and maintenance of BMPs are limited. New approaches, including watershed-based strategies for treating non-highway runoff outside the right-of-way are needed to economically implement BMPs that mitigate and control sources of runoff constituents.

The Stochastic Empirical Loading and Dilution Model (SELDM) was developed to simulate and provide risk assessment of concurrent downstream stormflow water-quality exceedances resulting from stormwater runoff. SELDM uses a Monte Carlo approach to estimate contaminant loads and concentrations from upstream basins and stormwater runoff, and can be a useful tool for decision-makers when evaluating alternatives for implementing BMPs for roadways and other developed areas.

The USGS Oregon Water Science Center, in cooperation with ODOT, conducted a study using SELDM in Oregon with three primary objectives: (1) to develop and demonstrate techniques that use the roadway and land use/land cover information from StreamStats and apply SELDM at selected points in the watershed; and (2) to demonstrate advanced methods for using SELDM to model the cumulative effects of runoff from different areas at different points in a watershed. SELDM is designed to provide for three general levels of analysis. These analyses can range in complexity from simulations done with pre-loaded regional statistics to analyses done with an extensive dataset collected at the site of interest. In theory, a level-three analysis using an extensive dataset collected at a site of interest would be best, but it can take years to collect representative data. Furthermore, such data may not represent conditions at the site of interest once the quality and quantity of runoff from the highway and the upstream basin change as a result of changes to the highway or upstream land use. Therefore, this report describes methods to adopt and adapt available data from hydrologically similar sites, by using comprehensive techniques to best represent conditions at a site of interest in Oregon.

For objective 1, a geographic information system (GIS) analysis of state roadways and upstream land uses and land covers was performed. Watersheds in western Oregon were grouped into narrow bands of drainage area to evaluate "typical" basin characteristics for watersheds of that size. Watersheds were screened for specific criteria; the Bear and Mill Creek watersheds were selected for further analysis. Seven road crossings were selected within each watershed for analysis using SELDM.

Precipitation statistics for the model runs were previously developed using the GIS data layers. The precipitation statistics were then modified by adjusting for mean annual precipitation using simple linear regression.

Prestorm streamflows statistics were generated with an index approach using regional streamgages with long-term records, and also streamgages of any length of record from within the watershed boundaries. Statistical relations were determined between the watershed drainage area at each crossing and the streamflow statistic of interest. Results were then adjusted based on residuals between the regional data and local data.

The stochastic-runoff coefficient statistics used in this analysis of highway-runoff volumes were calculated using the standard SELDM values. Average highway-runoff coefficients ranged from 0.506 to 0.785. For the non-highway-runoff volumes, statistics were calculated as a function of imperviousness. Average non-highway-runoff coefficients ranged from 0.129 to 0.177.

Eight regional watersheds with similar basin characteristics were used to estimate the coefficients needed for the SELDM hydrograph recession factor (HRF) module in the Bear Creek watershed. Regression relations were developed to estimate the minimum, most probable value and maximum HRF for each of the seven crossings in the Bear Creek watershed. The data from five regional streamgages were used in an identical approach for Mill Creek.

Three water-quality constituents were evaluated for this study—suspended-sediment concentration (SSC), total phosphorus (TP), and total copper (TCu). Highway runoff was simulated using the Highway Random runoff module in SELDM using event mean concentration (EMC) data collected from and screened by ODOT. Total suspended sediment (TSS) data were used to estimate SSC concentrations using MOVE.1, to supplement otherwise sparse SSC data, especially for highway runoff. Although TSS is a regulated constituent, the USGS has determined that it is fundamentally unreliable for measuring the amount of sediment in streams, and the literature indicates that this is accurate for highway and urban runoff as well. However, because TSS data are more commonly collected in relation to SSC data, it was surmised that using TSS data to estimate SSC values would add less uncertainty to model results than having less sediment data, and (or) having to use sediment data from locations that are less representative of the sites of interest.

A rank-correlation test was performed to evaluate the relation between average annual daily traffic and the statistics used to derive the EMC for water-quality constituents of highway runoff. Although the correlations appear strong, they were determined not to be significant at the 95th percentile. Consequently, highway-runoff values were not adjusted for average annual daily traffic.

Runoff statistics for developed areas were simulated using EMC data from the September 2016 version of the International Best Management Practice (BMP) Database. EMC statistics were grouped by land-use categories, but no clear relation was indicated between these categories and the magnitude of the geometric means. Consequently, in this study all developed areas were simulated together, rather than partitioning each specific land use. TSS data were used to augment the number of stations and EMCs of SSC. The Kendal-Theil Robust Line program was used to estimate the statistics of the logarithms of SSC from TSS statistic values from 14 sites with both TSS and SSC data, and the derived relation was used to transform data from other sites with only TSS data.

Transport curves were developed to relate streamflow to SSC and TP for minimally developed areas. For Mill Creek, these transport curves were developed using regional data from nearby stations with similar drainage characteristics indicative of largely undeveloped watersheds. For the Bear Creek watershed, the lack of streamflow productivity at the Bear Creek sites necessitated a more complex approach. A unique transport curve was developed for each site in the Bear Creek watershed by scaling the inflection and points of the regional transport curve developed by using the quantiles of streamflow productivity.

The upstream dependent water-quality module in SELDM was used to estimate TCu concentrations from SS concentrations. Because of limitations in SELDM, the resultant linear relation is a simplification that approximates best-estimate values of TCu, but is likely to show some bias for TCu values closer to the extremes on either end of the curve.

Runoff treatment was evaluated to measure the effects of BMPs on discharges to the receiving streams and on flows, concentrations, and loads of selected constituents in the receiving water downstream from the site of interest. A generic BMP was simulated using the SELDM BMP module. The median treatment statistics from nine BMP categories with data from the 2012 version of the International BMP Database were used to configure the BMP module.

Five simulation scenarios were performed to demonstrate potential uses of SELDM, the first two were designed for working within nested watersheds. The third, fourth, and fifth simulations were designed to investigate how changes made to particular parameters will effect concurrent downstream stormflow conditions. These last three simulations serve as a type of sensitivity analysis.

Instream EMCs were compared to hypothetical water-quality criteria for SSC, TP, and TCu to demonstrate the concept of water-quality risk analysis. These criteria were 80 milligrams per liter mg/L for SSC, 0.1 mg/L for TP, and 0.3 microgram per liter (µg/L) for TCu. All criteria were selected with consideration of local and (or) national standards, and other established criteria; however, selection of these criteria for use in this study does not indicate that the USGS has made analysis or conclusion about whether or not these criteria are protective of the designated uses or otherwise suitable for use in Oregon.

Simulation Scenario 1 was designed to represent the addition of a road crossing to an otherwise undeveloped watershed. Results indicated that for the Bear Creek watershed, a road crossing could be added to the Kirtland, Interstate-5, or Emigrant Creek at Highway 66 sites without expecting to exceed the TP criterion of 0.1 mg/L with a return interval 3 years. For the Mill Creek watershed, results indicate that the road crossing could be added to any of the five downstream sites and still be within the same criterion of exceedance, but would exceed the TP criterion at a greater frequency if placed at the Stayton or Boedigheimer Road site. Modeled upstream EMCs were similar to downstream EMCs at all sites for both watersheds, indicating that upstream EMCs play a large part in determining if TP criteria can be met, regardless of any new road crossing.

Model results indicate that it is impossible to meet the desired rate of exceedance of the TCu criteria (0.3 µg/L) for both watersheds because of the relatively high EMCs of concurrent upstream stormflow. However, exceedance rates did vary considerably based on location. Even though achieving the water-quality criterion may not be feasible in this scenario, the choice of placement of the new crossing would determine the rate of exceedance.

Model results indicate that achievement of the desired rate of exceedance for SSC could not be achieved in the Bear Creek watershed for any of the sites evaluated, although exceedance rates were much lower than those of TCu. For Mill Creek, the desired rate of exceedance for SSC could be achieved at any of the downstream five locations, similar to the results with TP.

All 14 model runs were also performed using the BMP module. Results indicate that generally only small rates of improvement were made for the frequency in which water-quality constituent criterion are exceeded. At one site (Hamilton Creek), model results indicate the implementation of a BMP would reduce the frequency of TP exceedances to less than the 3-year return interval standard.

Annual loading was largely a function of highway catchment size. Sites with the largest highway catchment area such as Bear Creek at Phoenix, Emigrant Creek at Highway 66, and the Mill Creek sites at Interstate-5 and Stayton have the largest annual water-quality constituent load productions relative to other sites within the Bear and Mill Creek watersheds.

Simulation Scenario 2 was designed to represent current conditions in the Bear and Mill Creek watersheds. The simulation was conducted in two parts—scenario 2A in which all of the developed (impervious) land upstream from the crossing is simulated by using the highway-site module in SELDM, and scenario 2B in which the concurrent downstream stormflow EMCs from scenario 2A are modeled as the concurrent upstream stormflow EMCs for scenario 2B and the standard highway approach is used.

The addition of the developed area greatly increased loading and the water-quality constituent EMCs of concurrent downstream stormflow, as was expected. Modeled increases were smallest at sites with relatively little upstream development, such as the Mill Creek at Boedigheimer Road and Emigrant Creek at Highway 66 sites. TCu criterion exceedance was very high at all sites in both watersheds.

The implementation of BMPs for Simulation Scenario 2A can serve as an upper bound for what reductions in EMCs and loading are theoretically possible. Conversely, implementation of a BMP for Simulation Scenario 2B is an analysis of runoff treatment for a specific road crossing. The implementation of BMPs resulted in the largest decrease in EMCs at locations with the smallest ratios of upstream drainage area to highway or urban runoff drainage area.

Overall annual loading was determined to be much larger in Simulation Scenario 2 than in Scenario 1, even with BMP implementation. The percent of annual loading of a water-quality constituent from the highway itself was calculated. Results greatly varied and were largely a function of the upstream and highway catchment drainage areas.

Simulation Scenario 3 was designed to evaluate the sensitivity of SELDM to various road layouts, by establishing one base location (Mill Creek at Turner) and using the highway site characteristics from other locations at the base location. The highway site configuration had low to moderate effects on modeled water-quality constituent EMCs of concurrent downstream stormflow. Conversely, annual loading from highway runoff, which is a function of the highway drainage area, exhibited much more variability. The Scenario 3 results indicate that different roadway configurations could be considered to minimize constituent loading.

Simulation Scenario 4 was designed to evaluate the sensitivity of one specific parameter road width, which determines the highway area simulated. Seven models were created with road widths between 16 and 112 feet in 16-foot increments. Similar to Scenario 3, varying the road widths resulted in little variation in water-quality constituent EMCs of concurrent downstream stormflow. Conversely, highway-runoff loads were directly proportional to road width. The results of this analysis show the importance of minimizing road width for reducing pollutant loading.

Simulation Scenario 5 was designed to evaluate the sensitivity of concurrent downstream stormflow constituent EMCs and loads to various amounts of impervious area upstream from the roadway of interest. The scenario was developed in a manner similar to Simulation Scenario 2A, but with upstream impervious area ranging from 5 to 30 percent. Both rates of water-quality constituent concentration exceedances and annual loading varied considerably. A correlation analysis of concurrent upstream stormflow, urban runoff, and concurrent downstream stormflow water-quality constituent EMCs using Kendall’s Tau shows that at low levels of impervious area (around 5 percent), the concurrent downstream stormflow has a slightly higher correlation to the concurrent upstream stormflow than the urban runoff. And as the percentages of urban areas increase, the correlation to the upstream stormflow is reduced as the correlation to the urban runoff increases. At an upstream imperviousness of 30 percent, the correlation to upstream runoff decreases to about 0.47 whereas the correlation to the urban runoff increases to about 0.74. The results from Simulation Scenario 5 can be used to understand the sensitivity of constituent EMCs to upstream development, and can be used as a weight for decisions on where to install a bridge, culvert, or BMP.

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