Prepared in cooperation with the Oregon Department of Transportation

Assessing the Impact of Chloride Deicer Application in the Siskiyou Pass, Southern Oregon

Scientific Investigations Report 2022–5091

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

Cover photographs (clockwise from left):

Flume at Carter Creek Branch 6, Oregon. Photograph by Tyler Kappen, U.S. Geological Survey (USGS), August 16, 2018.

Crest stage gage at Carter Creek Branch 6, Oregon. Photograph by Mark Schuster, USGS, November 2, 2017.

West Fork Ashland Creek, Oregon. Photograph by Bryan Coorlim, USGS, November 16, 2017.

USGS employee servicing gage at Carter Creek Branch 1, Oregon. Photograph by Bryan Coorlim, USGS, November 29, 2017.

Assessing the Impact of Chloride Deicer Application in the Siskiyou Pass, Southern Oregon

By Adam J. Stonewall, Matthew C. Yates, and Gregory E. Granato

Prepared in cooperation with the Oregon Department of Transportation

Scientific Investigations Report 2022–5091

U.S. Geological Survey, Reston, Virginia: 2022

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Suggested citation:
Stonewall, A.J., Yates, M.C., and Granato, G.E., 2022, Assessing the impact of chloride deicer application in the Siskiyou Pass, southern Oregon: U.S. Geological Survey Scientific Investigations Report 2022–5091, 94 p., https://doi.org/10.3133/sir20225091.

Associated data for this publication:
Stonewall, A.J., 2022, Stochastic Empirical Loading and Dilution Model (SELDM) model archive and instructions for the Siskiyou Pass, Oregon: U.S. Geological Survey data release, https://doi.org/10.5066/P9Q1PP61.

ISSN 2328-0328 (online)

Acknowledgments

The authors thank Jon Lazarus and Lynda Ogilvie from the Oregon Department of Transportation (ODOT). Mr. Lazarus was instrumental in supplying information and data to the authors in a timely manner and coordinating efforts between ODOT and the U.S. Geological Survey (USGS). Ms. Ogilvie compiled many pages of hand-written chloride deicer application logs into a useable electronic format resulting in data critical for calculating application rates along Interstate Route 5. Without Ms. Ogilvie's efforts, that entire section of this report would not have been feasible. The authors also thank the ODOT maintenance staff who compiled the logs, despite having to work in extreme weather conditions and at all hours of the day and night. The authors also thank Kira Glover-Cutter, William Fletcher, Patti Caswell, Jeffery Moore, Everett Carroll, and Bob Harshman, each of whom is either a current or former ODOT employee and contributed to this study by providing needed background about the study area, coordinating with the USGS on data collection, and (or) providing chloride deicer data from ODOT applications. Finally, the authors also thank all USGS employees who installed and maintained equipment, coordinated efforts with the authors, and collected data for this study, including Bryan Coorlim, Tyler Kappen, Marc Stewart, Frank Johnson, Mark Schuster, and Andy Erickson.

Contents

Figures

Tables

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)	3.785	liter (L)
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)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)

International System of Units to U.S. customary units

Multiply	By	To obtain
Volume		
liter (L)	0.2642	gallon (gal)
Mass		
milligram (mg)	0.00003527	ounce, avoirdupois (oz)

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

°F = (1.8 × °C) + 32.

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Supplemental Information

The models and the results of model simulations developed and used in this study are available from the U.S. Geological Survey ScienceBase web page at https://doi.org/10.5066/P9Q1PP61.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L) with the exception of specific conductance, which is given in microsiemens per centimeter (µS/cm) at 25 degrees Celsius.

Abbreviations

BMP	best management practice
BDF	basin development factor
CMC	criterion maximum concentration
EMC	event mean concentration
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
$MgCl_2$	magnesium chloride
NaCl	sodium chloride
NPDES	National Pollutant Discharge Elimination System
ODEQ	Oregon Department of Environmental Quality
ODOT	Oregon Department of Transportation
SELDM	Stochastic Empirical Loading and Dilution Model
USGS	U.S. Geological Survey

Assessing the Impact of Chloride Deicer Application in the Siskiyou Pass, Southern Oregon

By Adam J. Stonewall, Matthew C. Yates, and Gregory E. Granato

Abstract

Chloride deicers have been applied by the Oregon Department of Transportation (ODOT) to Interstate Route 5 (I–5) from the Oregon-California border north to mile marker 10 for several years in the high-elevation area known as the Siskiyou Pass. Magnesium chloride ($MgCl_2$) and sodium chloride (NaCl) are applied to keep the interstate highway safe for drivers and allow for efficient transport of goods and people through adverse weather conditions, particularly snow and ice. The U.S. Geological Survey entered into a cooperative agreement with ODOT to research the effects of chloride deicers in the Carter and Wall Creek watersheds that drain the vicinity of the Siskiyou Pass.

The Stochastic Empirical Loading and Dilution Model (SELDM) was used to estimate combinations of prestorm-streamflow, stormflow, highway-runoff, and event mean constituent concentrations (EMCs), as well as stormwater-constituent loads at sites of interest. The study evaluated the effects of roadway application of chloride deicers on downstream and highway-runoff conditions (particularly EMCs), exceedance rates of criterion maximum concentrations, and concurrent runoff loads of stormwater constituents from a site of interest. SELDM was also used to evaluate the efficiency of hydrograph extension best management practices to reduce peak constituent concentrations. Several SELDM scenarios were developed as sensitivity analyses to evaluate the model benefit of collecting specific local sets of data, such as streamflow, precipitation, highway-runoff and riverine water-quality samples, and volumetric runoff coefficient statistics.

Results of the study showed that for SELDM modeling in the Siskiyou Pass area, (1) the inclusion of local streamflow data is important for obtaining accurate downstream EMCs, (2) the inclusion of precipitation data is important for highway and concurrent runoff load calculations, and (3) water-quality constituent EMC data from highway runoff and upstream stormflows are the most important data to collect for highway runoff and upstream water-quality constituent concentration statistics.

Introduction

The Oregon Department of Transportation (ODOT) is charged with keeping Oregon's highways safe for motorists and keeping traffic moving efficiently regardless of weather conditions. Currently, ODOT relies on a proactive approach of applying a corrosion-inhibiting liquid deicer (magnesium chloride, or $MgCl_2$) to pavement prior to winter storms to prevent ice and snow from bonding to pavement. The application of $MgCl_2$ allows for more efficient plowing and snow removal during and after a winter storm and can be augmented with the addition of winter sand and gravel to improve traction. However, $MgCl_2$ does not function efficiently under all winter conditions (Salt Institute, 1991). Sometimes high application rates are needed to ensure that $MgCl_2$ is effective and that sand remains on the highway. High application rates result in higher costs, and under adverse weather conditions improvements in winter highway conditions are only marginal.

Sodium chloride (NaCl) is commonly used as a low cost, highly efficient winter maintenance tool for breaking up packed snow and ice, especially in States in the Midwest and Northeast (Kelly and others, 2010; Granato and others, 2015). Western States use NaCl for snow and ice mitigation as well, although historical use has not been as extensive owing to fewer highways and milder winters in many western locations. If application rates of NaCl can be lowered, it will result in less impact to the environment and less wear on highways. State DOTs commonly work a difficult balance between public safety and environmental, infrastructure, and material-cost concerns (Salt Institute, 1991).

ODOT has tried to avoid the use of NaCl entirely since the late 1990s because of concern about damage to concrete structures caused by the application of NaCl, and because research at the time indicated that chloride in NaCl disassociated more readily and was more mobile in the environment than chloride in $MgCl_2$. Of the two deicers, $MgCl_2$ is considered to be a more environmentally friendly alternative than NaCl (Shi and others, 2009). As a result, ODOT chose $MgCl_2$ as its primary highway deicer even though application of NaCl can be cheaper, easier, and more effective at reducing snow and ice on the highway (Salt Institute, 1991). Because of technical advancements by transportation agencies in reducing salt application rates and because of the winter safety and cost efficiencies that NaCl can provide, ODOT is currently experimenting with applying NaCl (in addition to $MgCl_2$) to some of its highways in winter. Adding NaCl to winter traction sand and gravel allows for the gravel to better imbed into the snow and ice, resulting in less gravel being projected from the roadway. By mixing solid NaCl with winter traction sand prior to highway application, ODOT hopes to reduce $MgCl_2$ application quantities and ultimately reduce the amount of chloride applied to ODOT highways, although the use of traction sand may have adverse effects on water quality and infrastructure (Smith and Granato, 2010; Smith and others, 2018). This use of NaCl should also improve mobility and winter driving conditions. California, Nevada, Idaho, and Washington all use NaCl as a primary deicer on their highways. By adding NaCl as a winter highway-maintenance tool, ODOT can make a smoother transition for vehicles as they move from NaCl to $MgCl_2$ maintained highways when crossing State lines.

A 5-year ODOT study (the Winter Salt Pilot Project) evaluating the use of NaCl for improving winter driving conditions ended in 2017. The project was designed to evaluate (1) the effectiveness of NaCl for improving winter driving conditions and (2) ODOT's ability to minimize adverse environmental impacts of the application of NaCl by developing and following appropriate chloride-application best management practices (BMPs). The preliminary findings of that pilot study were the impetus for this study and accompanying report.

NaCl has been applied on two stretches of highway: on Interstate Route 5 (I–5) at the Siskiyou Pass (fig. 1) between the California border and milepost 11, and on U.S. Highway 95 from the Oregon-Nevada border to the Oregon-Idaho border (approximately 121 miles of NaCl application, not shown). In coordination with the Oregon Department of Environmental Quality (ODEQ), ODOT has collected soil and water samples and has observed the roadside vegetation in both pilot areas to evaluate potential adverse environmental effects resulting from NaCl application.

The U.S. Geological Survey (USGS) entered into a cooperative agreement with ODOT to research the effects of chloride deicers in the Carter and Wall Creek watersheds, both of which drain within the Siskiyou Pass. Data collection spanned the period from November 2017 to November 2019 (water years 2018–20).

Oregon Department of Transportation Winter Salt Pilot Project

Preliminary unpublished findings from the ODOT Winter Salt Pilot Project (Jeffery Moore, Oregon Department of Transportation, written commun., 2017) have shown that application of NaCl in addition to ODOT's ongoing $MgCl_2$ application practices in two pilot areas has not produced observable effects on local vegetation, but stream sampling does indicate elevated chloride levels in both Wall and Carter Creeks in the Siskiyou Pass pilot area (near I–5 and the California border). ODEQ has set the chronic and acute water-quality criterion for chloride at 230 and 860 milligrams per liter (mg/L), respectively (Oregon Department of Environmental Quality, 2018). Elevated chloride values determined during the last 2 years of the pilot project (2014–15 and 2015–16) are of concern because they exceeded the above-referenced criteria for chloride.

The ODOT pilot project was designed to determine whether water-quality criteria were being exceeded in surface waters. However, the pilot project did not determine how much chloride infiltrated into the local groundwater system nor documented the environmental impacts resulting from long-term chloride dicer application (NaCl and $MgCl_2$) to the roads. Additional work is needed to evaluate these concerns and to determine whether the levels of chloride detected in the streams were from the pilot application of NaCl in conjunction with $MgCl_2$ or from the long-term application of $MgCl_2$ over the past 20 years.

USGS Stochastic Empirical Loading and Dilution Model

In cooperation with the Federal Highway Administration, the USGS developed methods for estimating pollutant loads and concentrations instream and from highway-runoff discharges to better manage highway stormwater. Using a Monte Carlo approach, the Stochastic Empirical Loading and Dilution Model (SELDM) estimates combinations of contaminant loads and concentrations from upstream basins and stormwater runoff affecting the water quality of receiving streams (Granato, 2006, 2008, 2010; Granato and Cazenas, 2009; Granato and others, 2009). Although SELDM is nominally a highway-runoff model, it is a lumped parameter model that can be used to model the quality and quantity of runoff from many land uses. By facilitating scenario simulation and sensitivity analysis, SELDM can determine the potential risk of downstream water-quality exceedances resulting from stormwater runoff.

SELDM can be run using national, regional, or local data. Local data are preferred if available. For model inputs where local data are not available, SELDM inputs are typically estimated using regional and (or) national data. For example, SELDM inputs require population statistics of the volumetric runoff coefficient (mean, standard deviation, and skew coefficient) for the highway crossing of interest. Because such data often are not available for the highway crossing of interest, the population statistics of the volumetric runoff coefficients are estimated based on the total impervious fraction of highway area. Other model inputs are estimated using regional and (or) national data in a similar manner. Much of the data collection in this study was designed to allow for local data to be input into SELDM rather than using regional or national data.

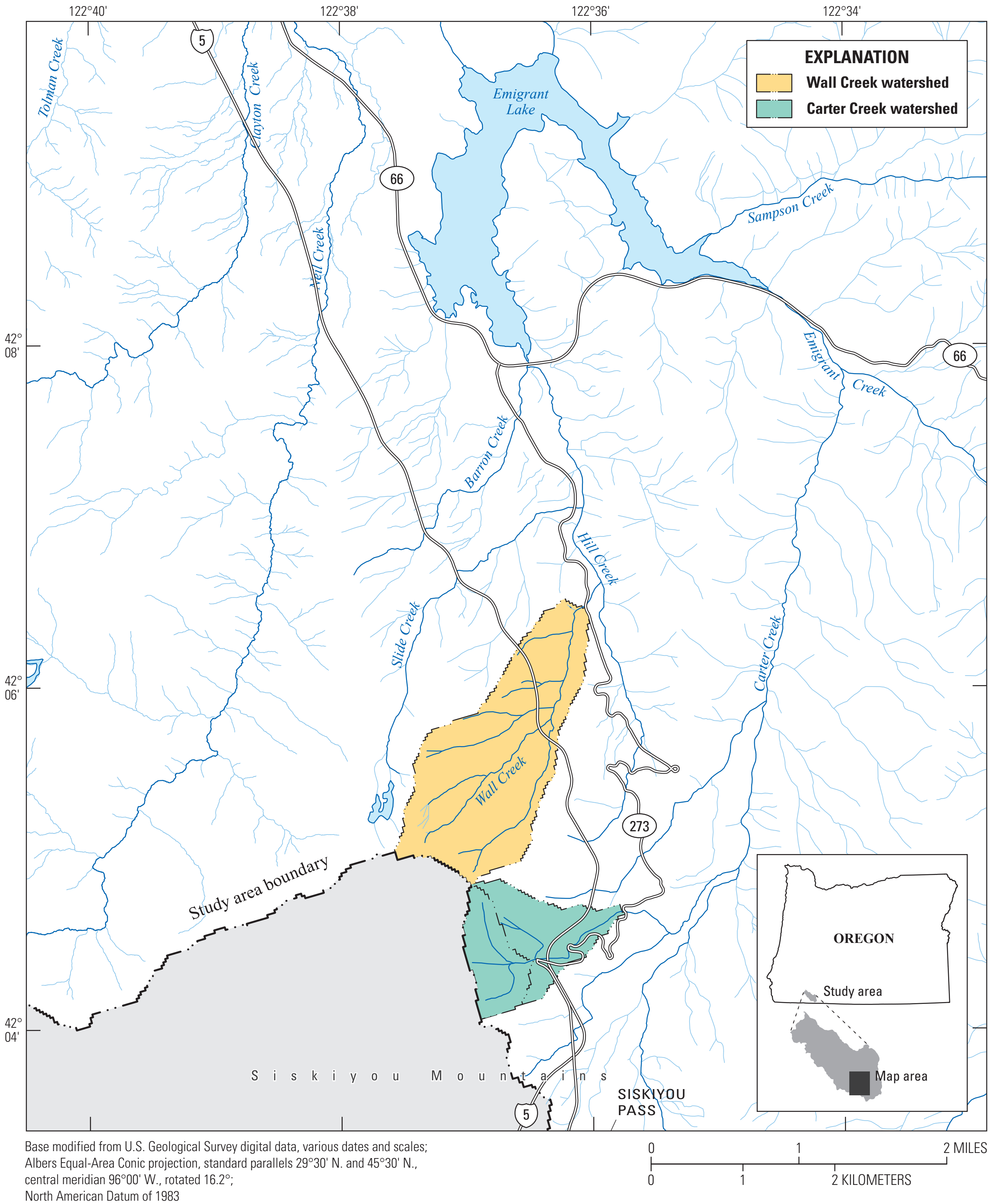


Figure 1. Carter and Wall Creek study area in the Siskiyou Pass, southern Oregon.

In the first of three ODOT-USGS research collaborations leveraging this method, SELDM was used to estimate storm flows and hypothetical constituent loadings and concentrations in six Western Oregon highway study sites with upstream watersheds ranging from 0.16 to 6.56 square miles (mi^2) (Risley and Granato, 2014). A second ODOT-USGS study applied SELDM to watersheds having multiple ODOT roadways crossing a single stream for evaluation and quantification of the contribution of stormwater from State roadways to the pollutant load of an entire watershed (Stonewall and others, 2019). This study is the third ODOT-USGS research collaboration involving SELDM.

Purpose and Scope

This report documents multiple analyses made using SELDM to evaluate effects of the application of chloride deicers near and along I–5 in the Siskiyou Pass—specifically in the Carter and Wall Creek watersheds. The primary objectives of the study included the following:

1. Use SELDM to evaluate the amount of chloride that will reach Carter and Wall Creeks for a given amount of chloride-based deicers applied to roadways. Specifically, to use SELDM to calculate the probability of exceeding water-quality standards in a given year.
2. Use SELDM to evaluate the use of chloride-application BMPs to mitigate the effects of using chlorides.
3. Use collected data to analyze how much of the chloride downstream is from NaCl and $MgCl_2$, respectively.
4. Evaluate the use of SELDM using different combinations of locally collected data and historical regional data to determine which locally collected data are most beneficial for model accuracy and which locally collected data are adequately represented by regional estimations without additional data collection.
5. Evaluate expected background levels of chloride, magnesium, and sodium in streamflows for the region assuming no anthropogenic inputs.
6. Evaluate the expected percentage of deicer chlorides applied to roadways that will reach receiving waters.

Terminology

The following terminology, much of which is taken from Risley and Granato (2014), Stonewall and others (2018), and Stonewall and others (2019), is used throughout this report:

Concurrent runoff is the runoff that occurs when there is measurable runoff in both the stream and from the highway, as measured downstream from the highway unless otherwise noted. Note that concurrent runoff is often much smaller than total annual runoff, which can include periods when there is streamflow but no highway runoff. For this study area, one common example of this scenario would be instances in which the highway and right of way are snow-free, but there is snowmelt feeding local streams. Thus, ***concurrent runoff load*** represents the total load that occurs collectively only during periods of concurrent runoff. For this report, concurrent runoff loads are usually expressed for annual periods (pounds per year).

Criterion maximum concentration (CMC) is an estimate of the highest concentration of a water-quality constituent to which an aquatic community can be exposed briefly without resulting in an unacceptable effect. For this study, non-chloride CMCs are hypothetical, and not based on known studies.

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.

Exceedance probability is the probability that a given value (usually an EMC for this study) will be equaled or exceeded. For example, if the exceedance probability is 0.40 for a chloride EMC of 10 mg/L, this means that in 40-percent of occurrences, the chloride in question will be equal to or greater than 10 mg/L.

Dilution factor in the SELDM model is the highway runoff or BMP-discharge volume (in cubic feet [ft^3]) divided by the downstream stormflow concurrent with the highway runoff or BMP discharge (in ft^3).

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

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

Hydrograph extension is an increase in the duration of discharge of highway runoff beyond the length of a storm achieved by using a structural BMP. In other words, a BMP is constructed in such a manner as to spread out the discharge over a longer period of time, which is intended to result in smaller peak discharges from the highway to the receiving water.

Road (or highway) crossing is the point of intersection between the stream of interest and a road. It could be a bridge or a culvert. The term can be considered synonymous with “stream crossing,” although the latter term was avoided in this report for consistency and because streams may cross other structures such as railroad tracks and pipelines, which may be sources of other constituents of concern but are not typically subject to high chloride application.

Stormflow is the surface-water runoff derived from a precipitation event. In SELDM, stormflows in runoff conveyances and structural BMPs comprise concentrated land-surface runoff and potentially groundwater or vadose-zone discharge. Stormflows in receiving waters comprise stormflows from runoff sources and prestorm flows, which may be base flow if the time between events is sufficient for the previous storm to recede, or base flow plus the remaining stormflow from the previous event.

Volumetric runoff coefficient is the percentage of precipitation that becomes runoff for a given catchment. For this project, such runoff would either be in the form of stormflow in a stream or highway runoff that reaches a stream. For example, if 100,000 ft^3 of precipitation fell over the watershed for one storm event and 30,000 ft^3 of that precipitation reached the stream and became stormflow, the volumetric runoff coefficient would be 0.3 or 30 percent.

In statistics, the ***population*** is the total membership of a defined class of people, objects, or events. For example, the set of measured concentrations of chloride in runoff in selected events from a specific highway would be a sample for that site, but a set of measured concentrations from all events would be considered a population of concentrations. Few sampling programs can measure a population of events, but a Monte Carlo model can simulate a population by using sample statistics. Both the sample and the population share membership of being from the same physical location (a specific highway) and are of the same type of event (highway-runoff concentrations).

For purposes of this report, ***exceedance*** is the occurrence of a number of events or a period of time in which a specific value is exceeded. Similarly, ***exceedance probability*** is the probability of exceeding a value for a given number of events or duration of time. In this report, exceedance probability will most commonly be used to denote the probability of exceeding a water-quality standard for any storm event, unless denoted otherwise (for example, “annual exceedance probability”). Note that in some literature, the terms “fraction of events that equal or exceed a given value” and “excursion probability” are used in a manner that is synonymous with how “exceedance probability” is used in this report.

The terms ***road*** and ***highway*** are used interchangeably in this report and represent the paved, impervious transportation corridor onto which the deicer is applied.

SELDM Background

SELDM was developed to estimate the risk of exceeding specific stormwater concentrations, flows, and (or) water-quality 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 was designed to provide long-term planning-level estimates of constituent loads and EMCs, the results of which can then be used to assess and evaluate alternative management scenarios. However, planning-level estimates 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 at individual monitoring sites. SELDM simulations can be used to estimate downstream water-quality constituent EMCs, provide an example concentration risk analysis, and produce estimates of long-term loads.

SELDM is a stochastic model that uses Monte Carlo methods to produce random combinations of input variables needed to generate a stochastic population of values for each component variable. SELDM results are ranked, and plotting positions are calculated to indicate the level of risk of adverse effects caused by constituent runoff concentrations, flows, and loads on receiving waters by storm and by year. SELDM is not a deterministic hydrologic model, and consequently is not calibrated by changing values of input variables to match a historical record of values. Instead, input values for SELDM are based on site characteristics and representative statistics for each hydrologic variable. As such, SELDM is an empirical model based on data and statistics rather than theoretical physiochemical equations.

SELDM is a lumped-parameter model because the highway site and the upstream basin are each represented as a single homogeneous unit. Each source area is represented by average basin properties, and results are calculated as point estimates for the site of interest. SELDM is designed to provide for three general levels of analysis. As noted in Stonewall and others (2019), p. 5:

> “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."

SELDM was designed to allow different levels of analysis for just this reason; if a quick regional analysis indicated that the risks for adverse effects of runoff are remote, a level-1 analysis may be sufficient, but if the risks are substantial, then a more detailed analysis (level-2 or 3) may be warranted (Granato, 2013). Such an approach is needed by State departments of transportation and municipalities that have extensive road networks that may cross and (or) discharge into many streams. For example, the National Bridge Inventory indicates that ODOT maintains 8,211 bridges in the State; although some of these bridges may cross roads and railways, this number does not include many more culverts that also cross streams (Federal Highway Administration, 2020).

Because SELDM does not incorporate seasonality into its modeling structure, and because the salinity of paved-area runoff typically varies through the course of melt events, the EMCs estimated by SELDM may not fully represent the bimodality of the population of EMCs. As a result, individual EMCs may exceed SELDM estimates at low exceedance probabilities. However, because SELDM inputs replicate EMC population statistics, the resulting model constituent loads should balance out over time.

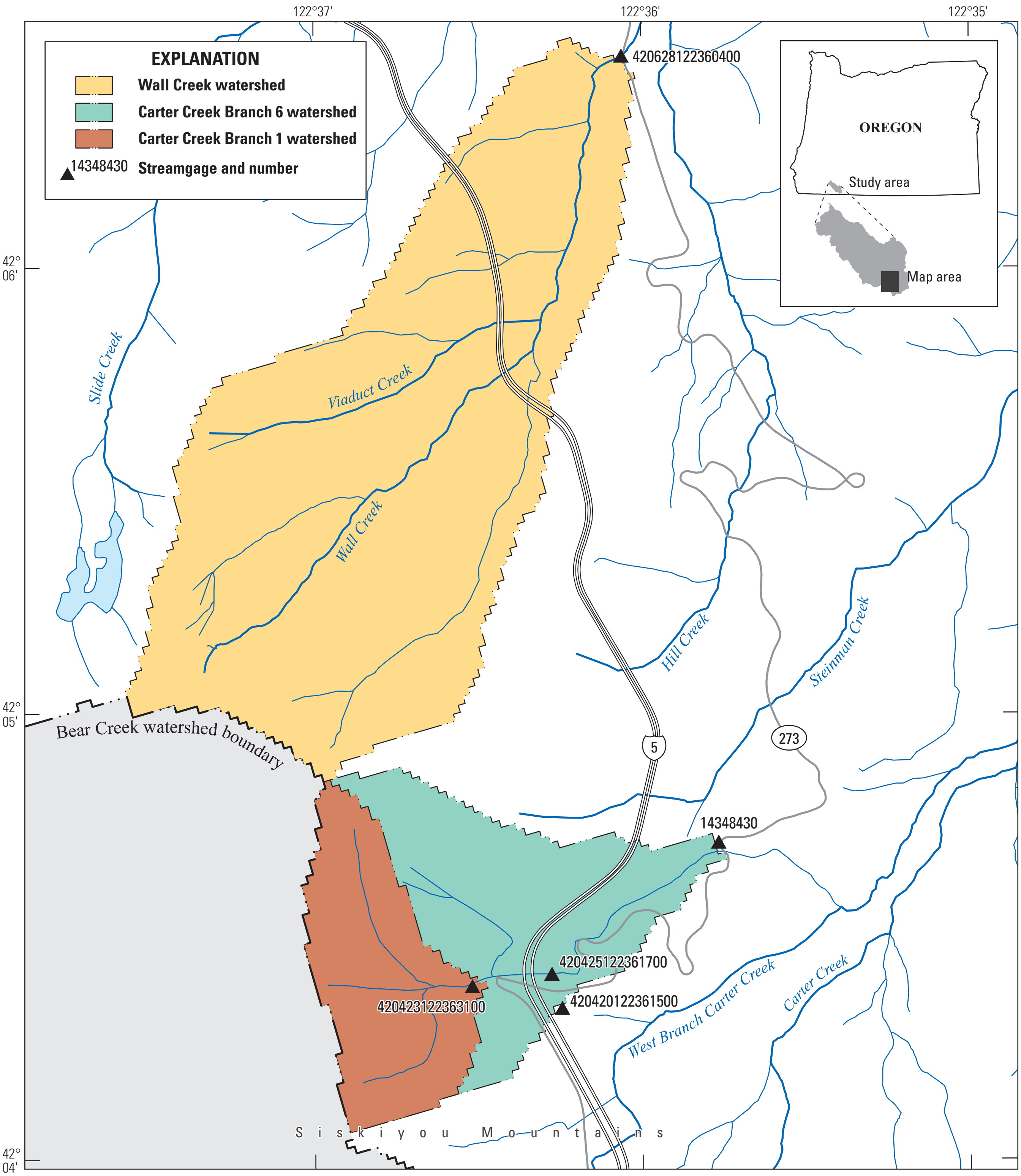
Hydrologic Setting

The Carter and Wall Creek watersheds are located in southern Oregon, along the I–5 corridor in the Siskiyou Mountains (fig. 1). Carter Creek has a drainage area of about 8.9 mi^2, most of which is downstream of its crossing with I–5. Carter Creek is a tributary to Emigrant Creek, which flows into Emigrant Lake, which is a part of the Bear Creek watershed. Carter Creek has many branches and unnamed tributaries, including the West Branch. Four branches of Carter Creek cross I–5, of which only the West Branch is officially named. For this study, all branches of Carter Creek were assigned a number (fig. 2). The primary focus of this report will be Branch 1 (a tributary to the West Branch), as it is the only perennial stream branch of Carter Creek to cross I–5 and is located in an area with relatively heavy road-deicer application compared to the rest of I–5. More basin characteristics for the Carter Creek watershed upstream from I–5 and Oregon State Route 273 can be found in table 1, including the length of minor, major, and State roads within the watersheds.

Wall Creek has a drainage area of about 1.3 mi^2, of which about 0.9 mi^2 is upstream from I–5 (which is the location in table 1). Wall Creek is a tributary to Hill Creek, which is a tributary to Emigrant Lake. Wall Creek has two minor branches that converge near I–5.

The geology of the study area can be roughly partitioned using the path of I–5 and the location of the Siskiyou Summit. South of Ashland along the I–5 corridor is the undivided, metamorphic amphibolite and schist of the Applegate Group (Wells, 1956). Northeast of the highway is the Hornbrook Formation, a collection of Cretaceous marine sedimentary rocks. A small outcrop of the Osburger Gulch Sandstone Member of the Hornbrook Formation is located near the Siskiyou Summit (Nilsen, 1993). Eocene sedimentary rocks make up the Payne Cliffs Formation, which are located to the east of the Hornbrook Formation. The southeast section of the study area is composed of the Oligocene-Miocene Little Butte Volcanics basaltic andesite, andesite, and volcaniclastic rocks of the Roxy Formation. To the southwest are the volcaniclastic rocks of the Eocene-Oligocene Colestin Formation, part of the Western Cascade Volcanics (Kays, 1970; Bestland, 1987). To the northwest is the Jurassic biotite granodiorite and granite of the Ashland pluton. Numerous Quaternary surficial deposits and landslides are scattered throughout the study area.

Mean annual precipitation for the Carter and Wall Creek watersheds is about 25.7 and 27.5 inches, respectively. Much of this precipitation falls as snow, as both watersheds have mean elevations of more than 3,500 ft (3,540 ft for Carter Creek and 4,270 ft for Wall Creek). Precipitation patterns are characteristic of a Mediterranean climate, with warm, dry summers and cool, wet winters.



Base modified from U.S. Geological Survey digital data, various dates and scales;
Albers Equal-Area Conic projection, standard parallels 29°30' N. and 45°30' N.,
central meridian 96°00' W., rotated 16.2°;
North American Datum of 1983

Figure 2. Carter Creek study areas adjacent to Interstate Route 5 in the Siskiyou Pass, southern Oregon.

Table 1. Basin characteristics of Carter Creek Branches 1 and 6, and Wall Creek in the Siskiyou Pass, southern Oregon.

[NAD 83, North American Datum of 1983; I–5, Interstate Route 5; –, not applicable]

Basin characteristic	StreamStats basin characteristic	Units	Carter Creek Branch 1 (420425122361700)	Carter Creek Branch 6 (14348430)	Wall Creek (420628122360400)
Description of most downstream point in basin	–	–	Intersection of Carter Creek Branch 1 and I–5	Intersection of Carter Creek Branch 6 and Oregon State Route 273	Intersection of Wall Creek and I–5
Latitude/longitude coordinates (highway crossing) of StreamStats delineation point	–	Decimal degrees, NAD 83	42.0707, –122.6013	42.07794, –122.59609	42.09825, –122.60528
Drainage area	DRNAREA	Square miles	0.246	0.58	0.91
Mean basin slope	BSLOPD	Degrees	19.8	19.2	21.4
Mean basin elevation	ELEV	Feet	4,640	4,440	4,310
Max basin elevation	ELEVMAX	Feet	5,620	5,620	5,840
Forest	LC11FORSHB	Percent	83	73	87
Impervious	LC11IMP	Percent	0.73	5.23	1.64
Length of non-State minor roads in basin	MIN_ROADS	Miles	0.13	0.33	0
Length of non-State major roads in basin	MAJ_ROADS	Miles	0.47	0.47	0
Length of State highways in basin[1]	STATE_HWY	Miles	0.00	2.00	1.51

[1]These basin characteristics represent the drainage area just upstream from the highway intersections. For example, Carter Creek Branch 1 is the watershed just upstream from I–5, which is why the length of State highways in the basin is zero.

Acquisition of Local Hydrological and Meteorological Data

As part of the study, local hydrological and meteorological data were collected in the Siskiyou Pass (fig. 2, table 2). Precipitation data were collected just south of the highway-runoff gage at USGS station 420420122361500 on the other side of Oregon State Route 273. Precipitation was collected in a heated rain gage, meaning that all precipitation was recorded as liquid water equivalent rather than snow. Local temperature records can be used to infer whether specific precipitation events fell as rain or snow. Precipitation data were used from the 2-year period of November 7, 2017, to November 6, 2019.

Highway-runoff flow data were collected in the “cloverleaf” just north of Oregon State Route 273 (also known as Old Highway 99) between I–5 and the interstate offramp as it circles back toward Oregon State Route 273 (USGS station 420425122361700). The runoff from the highway flows into the southeast section of the partial cloverleaf intersection and through a weir constructed by the USGS (fig. 3). From there the runoff flows through a large grate and into an unnamed tributary to Carter Creek (named as Branch 1 for this report). Flow measurements of the highway runoff were made near the weir, and 15-minute stage values were recorded in the pool behind the weir (U.S. Geological Survey, 2020a). A stage-discharge relation was developed from the flow measurements and the stage record. Specific conductance was also collected at this location. Additionally, an autosampler was set up (fig. 4) to collect water samples during large storm events. The sampler was programmed to trigger according to specific conductance readings. The autosampler collected 518 samples over the course of 70 events (U.S. Geological Survey, 2020b). All instrumentation was positioned just upstream from the weir.

Streamflow data were collected just upstream from the intersection of Oregon State Route 273 and the unnamed tributary to Carter Creek (USGS station 14348430). A traditional USGS stage-discharge rating was developed using the stage data and instantaneous measurements and streamflow (U.S. Geological Survey, 2020c). Continuous specific conductance data were collected at this site. In the winter of 2018–19, an autosampler was installed at this site to collect water samples during large events related to snowmelt (U.S. Geological Survey, 2020d). Autosampler samples were analyzed for specific conductance, chloride, magnesium, and sodium. Streamflow and specific conductance data from November 9, 2017, to November 8, 2019, were used for analysis in this study.

Additional specific conductance data were collected on Wall Creek just upstream from Oregon State Route 273 (USGS station 420628122360400) and upstream from I–5 on the unnamed tributary to Carter Creek that runs through the partial cloverleaf near Oregon State Route 273 (USGS station 420423122363100). Data were collected at these sites from October 27, 2017, to June 11, 2019. Because these specific conductance records were less than 2 years in length, data for the missing period (June 12–October 26, 2019) were estimated using data from 2018. Because the period of incomplete data occurred during summer, when chloride application and flow rates are low, the absence of this part of the record was surmised to have minimal impact on results.

In addition to samples collected using the two autosamplers, water samples were manually collected at several locations in the Bear Creek watershed (fig. 5, table 2). Most samples were collected outside of the Carter and Wall Creek watersheds to evaluate background levels of the three major ions of interest (chloride, magnesium, and sodium). Samples from the Carter and Wall Creek watersheds (around the locations in table 1) were also collected for use in SELDM.

Table 2. Hydrologic and meteorological data collected by the U.S. Geological Survey (USGS) in the Carter and Wall Creek watersheds in the Siskiyou Pass, southern Oregon, 2017–19.

[NAD 83, North American Datum of 1983; GH, gage height; Q, discharge; SC, specific conductance; AS, autosampler; MAN, manual samples; P, precipitation; NHDPlus, National Hydrography Dataset Plus; I–5, Interstate Route 5; Hwy, Highway; Trib, Tributary; Or, Oregon; Nr, near; Wbr, West Branch; abv, above; Rd, Road; St, Street; Dr, Drive; Cr, Creek; Mem, Memorial; Ln, Lane; E, East; W, West; WF, West Fork]

USGS station name	USGS station number	Latitude (NAD 83)	Longitude (NAD 83)	Data collected	Notes or NHDPlus stream order
Carter and Wall Creek watersheds					
Highway Runoff Site Nr I5 and Old Hwy 99	420425122361700	42.07358	–122.6047	GH, Q, SC, AS	Highway runoff that enters Carter Creek Branch 1
Unnamed Trib to Wbr Carter Creek, near Ashland, Or	14348430	42.0785	–122.5962	GH, Q, SC, AS	Carter Creek Branch 6
Wall Creek near Ashland, Or	420628122360400	42.10789	–122.601	SC, MAN	
Unnamed Trib to Wbr Carter Cr abv I5 Nr Ashland, Or	420423122363100	42.07313	–122.6087	SC, MAN	Carter Creek Branch 1
Precipitation nr I5 And Old Hwy 99, Nr Ashland, Or	420420122361500	42.07231	–122.6041	P	
Other Bear Creek watersheds					
Anderson Creek at Hwy 99, Phoenix, Or	421600122482701	42.26655	–122.8074	MAN	2
Arrastra Creek nr Wagner Creek Rd, nr Ashland, Or	421050122465500	42.18053	–122.7821	MAN	1
Ashland Creek near Nutley St, Ashland, Or	421140122430001	42.19456	–122.7167	MAN	3
Bear Creek near Alba Dr, Medford, Or	421903122511301	42.31764	–122.8535	MAN	4
Dean Creek at I5, near Seven Oaks, Or	422421122563300	42.40592	–122.9424	MAN	1
Emigrant Cr at Dead Indian Mem Rd, nr Ashland, Or	421134122390501	42.19271	–122.6514	MAN	4
Gore Creek at Lowry Ln, at Medford, Or	421808122504400	42.30225	–122.8455	MAN	1
Griffin Creek at Hwy 238, near Medford, Or	422027122552801	42.34079	–122.9244	MAN	2
Jackson Creek at E California St, Jacksonville, Or	421856122582001	42.31557	–122.9721	MAN	3
Jeffery Creek at Dump Road, near Talent, Oregon	421545122440801	42.26237	–122.7355	MAN	1
Larson Creek at Golf View Dr, at Medford, Or	421847122492300	42.31314	–122.823	MAN	1
Lazy Creek at Murphy Road, Medford, Or	421920122494401	42.32218	–122.8289	MAN	1
Murphy Creek at Griffin Ln, nr Medford, Or	421540122552900	42.26117	–122.9248	MAN	1
Myer Creek at I–5, near Talent, Or	421402122451101	42.23398	–122.7531	MAN	2
Neil Creek at Reiten Dr, near Ashland, Or	420906122375900	42.15169	–122.633	MAN	1
Spring Creek at Emigrant Creek Rd, near Ashland	420350122325400	42.06397	–122.5483	MAN	1
Tolman Creek at Tolman Creek Rd, nr Ashland, Or	420903122403201	42.15087	–122.6754	MAN	1
Tyler Creek at Baldy Creek Road, nr Ashland, Or	420651122295401	42.11423	–122.4982	MAN	1
Wagner Creek at W Valley View Rd, at Talent, Or	421445122464800	42.24569	–122.7801	MAN	2
WF Ashland Creek at Horn Creek Rd, nr Ashland, Or	420623122444500	42.10631	–122.7457	MAN	1

Figure 3. Weir used for highway-runoff flow measurement into Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon. [Photograph by Mark Schuster, 2018, U.S. Geological Survey.]

Figure 4. Autosampler used to sample highway runoff into Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon. [Photograph by Mark Schuster, 2018, U.S. Geological Survey.]

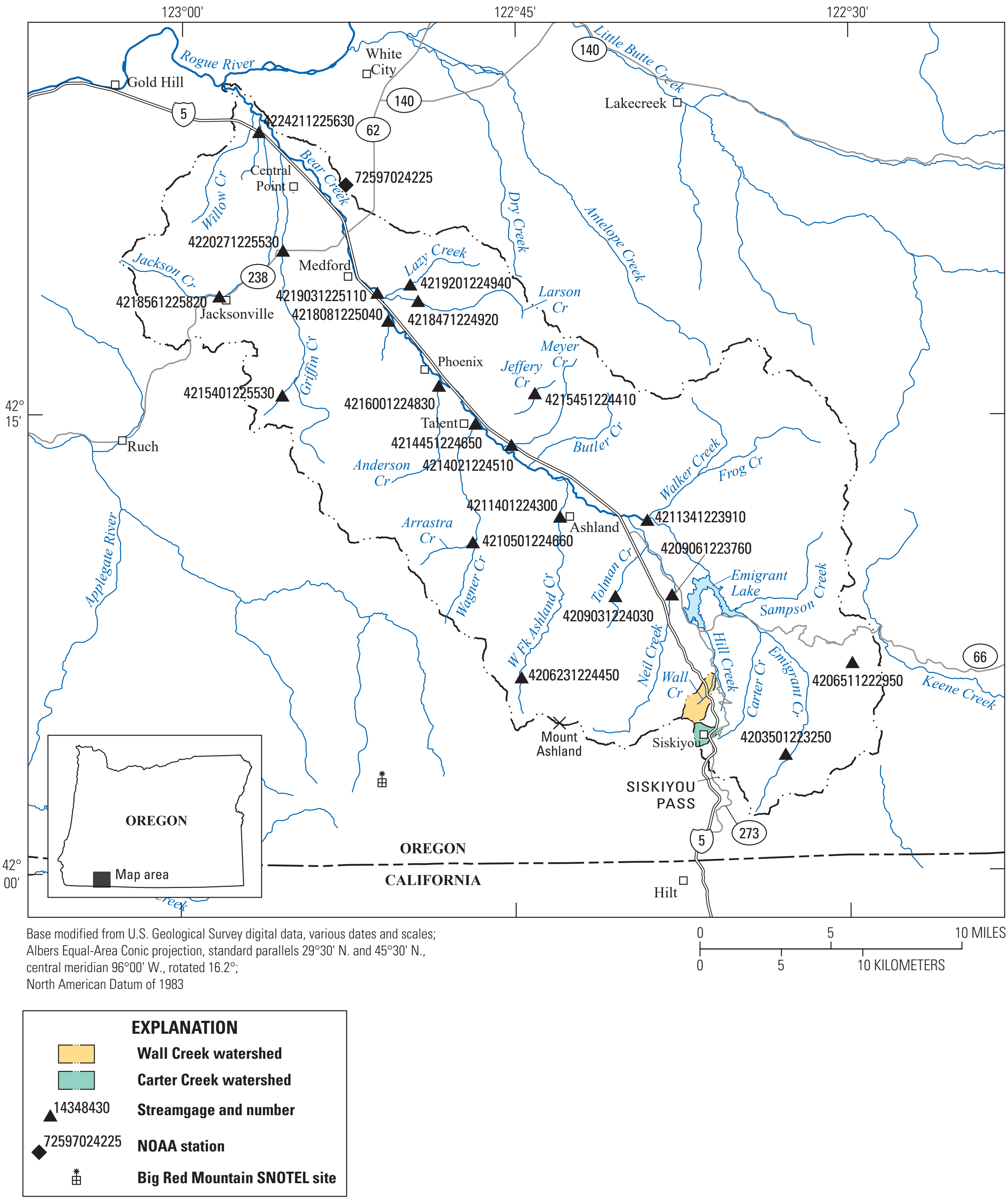


Figure 5. Locations of water samples collected manually from the Bear Creek watershed in southern Oregon. [NOAA, National Oceanic and Atmospheric Administration.]

Regional Background Concentrations of Chloride, Magnesium, and Sodium

To estimate regional background concentrations of chloride, magnesium, and sodium, water samples were collected from 20 random sites within the Bear Creek watershed during the low-flow fall season of 2018 (table 2 and fig. 5). All background stream samples were taken just upstream from roadway crossings. A geographic information system (GIS) analysis was used to determine where to collect random samples with the following methodology:

1. The NHDPlus hydrologic dataset (U.S. Environmental Protection Agency, 2021a) was downloaded and cropped to include only flow pathways within the Bear Creek watershed.
2. All waterways that did not represent relatively natural waterways were removed from analysis. For example, any waterways specified as a “Canal Ditch” were removed.
3. The “ORTRANS_public” database (Oregon Spatial Data Library, 2017) was downloaded and cropped to include only roads within the Bear Creek watershed.
4. All intersections between public roads and natural waterways were mapped. Public roads were deemed necessary for access to the waterways.
5. For every intersection between a waterway and a road, the National Hydrology Dataset Plus or NHDPlus stream of the waterway was determined. Waterways of stream order “zero” were eliminated from consideration because they are small enough that they would likely be dry during sampling.
6. For each stream order (first, second, third, and fourth), the number of road crossings was tabulated. The number of samples for each stream order was determined by the percentage of intersections that had streams of that stream order. For example, 95 of the total 489 intersections were with second-order streams, which represents about 19 percent of all intersections. Consequently, 4 (19 percent of 20 samples) samples should be collected from second-order streams. The final results were 12 first-order stream intersections, 4 second-order stream intersections, and 2 intersections with both third- and fourth-order streams.
7. For each of the four stream orders, all stream intersections were ranked using a random number generator.
8. During sampling, if any streams were found to be dry or unreachable, the next stream of the same stream order with the next-highest randomly generated number was sampled instead.

Median values of chloride, magnesium, and sodium were 11.4, 14.7 and 16.9 mg/L, respectively (fig. 6). The median specific conductance of all samples was 404 microsiemens per centimeter (µS/cm) at 25 degrees Celsius. One sample site of note is Jeffery Creek at Dump Road (USGS station 421545122440801). As the name implies, the creek runs through a waste disposal site. Landfill sites have been documented as sources of chloride (Granato and others, 2015). The Jeffery Creek site had the highest concentrations of chloride, magnesium, and sodium, and the highest specific conductance value of any of the manual grab samples made for estimating regional background concentrations.

Linear regression analysis on the logarithms of data showed strong correlation between specific conductance values and all three ions of interest (fig. 7), with r-squared values ranging from 0.71 to 0.96. Of the three ions investigated, magnesium had the strongest correlation with specific conductance.

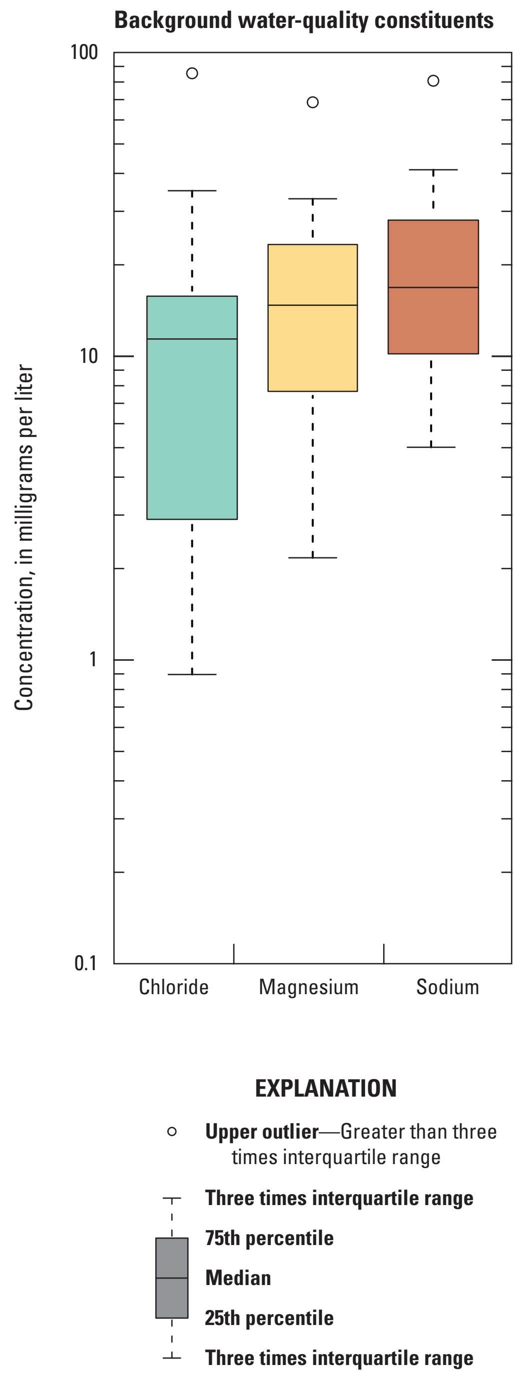


Figure 6. Statistical distribution of chloride, magnesium, and sodium concentration data from water samples taken in the Bear Creek watershed, southern Oregon.

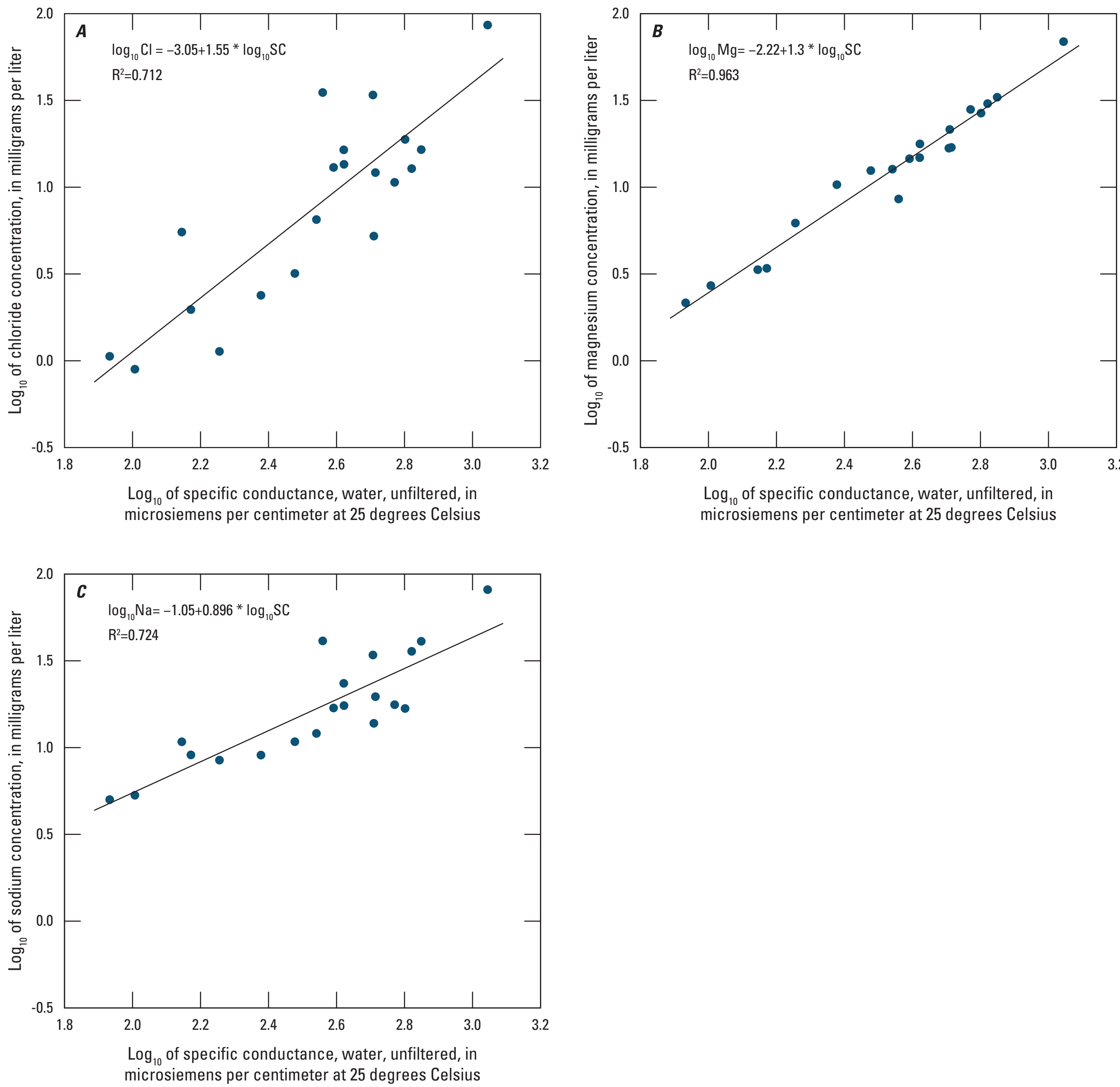


Figure 7. Relation between specific conductance and (*A*) chloride (Cl), (*B*) magnesium (Mg), and (*C*) sodium (Na) concentrations in the Bear Creek watershed, southern Oregon. [R^2, coefficient of determination.]

Development of SELDM Scenarios

SELDM produces a random collection of events developed to be representative of long-term site conditions rather than a series of historical events that follow seasonal patterns. For this project, each SELDM scenario simulates 39 years of data across 1,300 to 1,600 individual storm events. All SELDM scenarios developed in this study are available from the USGS ScienceBase web page (Stonewall, 2022).

Fifteen SELDM scenarios were developed (1) to estimate water-quality constituent concentrations, concurrent runoff loading, and criterion maximum concentration (CMC) exceedances at three locations (table 1) and (2) to perform sensitivity analyses on the inclusion of a specific set of local data (table 3). One or more sets of inputs were developed for each set of parameters needed to perform SELDM runs: highway-site characteristics, upstream basin characteristics, precipitation statistics, streamflow statistics, volumetric runoff coefficient statistics, and water-quality statistics. Each SELDM scenario is a unique combination of these input sets.

Calculation of Highway Site Characteristics

SELDM requires five highway site characteristics for calculations of highway stormflow runoff (table 4). Four of the characteristics—drainage area, drainage length, mean basin slope and impervious fraction—can be calculated using a combination of standard GIS software, aerial photography, highway engineering designs, and physical observations of the highway catchment. The drainage area determines the precipitation volume that falls on the highway catchment during each event. Drainage length, mean basin slope, and the basin development factor determine the timing of the runoff hydrograph. The impervious fraction determines the volumetric runoff coefficient statistics, which are used to translate the precipitation volume into a runoff volume. These four characteristics do not vary according to the level of analysis because they are derived from actual site conditions. In other words, the characteristics are identical for a level-1, level-2, or level-3 analysis.

The basin development factor (BDF) was developed for small stream basins by Sauer and others (1983) and has been adapted for SELDM use to be a representation of general development and urban highway infrastructure within the highway catchment, with a scale of ratings from 0 to 12, the higher BDF values representing more urban development and infrastructure, and less infiltration. BDF is used to calculate the basin lag time and can be calculated using one of two methods. The BDF value can be estimated by inventorying channel improvements, channel lining, storm drains, storm sewers, and curb-and-gutter streets. For this study, this inventory approach was considered a level-3 analysis. SELDM also allows the user to enter a BDF value of -1, which results in SELDM computing catchment lag times using regression equations relating lag time to total impervious area. Granato (2012) showed that BDFs are highly correlated with total impervious area. For this study, the automated approach to BDF calculation was considered a level-1 analysis.

Table 3. List of Stochastic Empirical Loading and Dilution Model (SELDM) scenarios and input short names for Carter and Wall Creek watersheds in the Siskiyou Pass, southern Oregon.

[Table 3 (in the form of Microsoft Excel and .csv files) is available for download at https://doi.org./10.3133/sir20225091.]

Table 4. Highway site characteristics needed for Stochastic Empirical Loading and Dilution Model highway-runoff calculations.

[BDF, basin development factor]

Site characteristic	Units	Carter Creek Branch 1	Carter Creek Branch 6	Wall Creek
Highway drainage area	Acres	8.74	13.23	8.2
Drainage length	Feet	993.7	993.7	2,375
Mean basin slope	Feet per mile	412.44	412.44	334.48
Impervious fraction	No units	0.3741	0.3044	0.99
BDF 1st order	No units	–1	–1	–1
BDF 3rd order	No units	8	8	9

Calculation of Upstream Basin Characteristics

SELDM requires eight upstream basin characteristics to estimate stormflow (table 5). Five upstream basin characteristics are related to basin hydraulics. Drainage area, mean basin slope, and impervious fraction can be calculated using the Oregon StreamStats web page (U.S. Geological Survey, 2018a). Drainage length can be calculated using standard GIS software. Similar to the highway site characteristics, these four characteristics do not vary according to the level of analysis.

The fifth hydraulic basin characteristic, BDF, is similar to the highway BDF. It can be calculated using the approach detailed by Sauer and others (1983) (used for level-2 and level-3 analyses) or by entering a BDF value of –1 (which calculates the basin lag time by using the impervious fraction of the basin, which was used for level-1 analysis).

The remaining three upstream basin characteristics are hydrograph recession variables, which, with the basin lag factor, determine the timing of stormflows from the upstream basin (Granato, 2012). Hydrograph-recession variables were calculated using three methods, depending on the analysis level. The level-1 analysis uses the default values for all three characteristics. These hydrograph-recession parameters are calculated using the median values of a nationwide database of USGS streamgages.

For the level-2 analysis, records from nearby streamgages having significant record length (more than 5 years) and similar basin characteristics that would influence hydrograph shape (drainage area, slope, and elevation) were analyzed (table 6). For three sites meeting these requirements, a series of hydrographs were analyzed for shape, including the ratio of the durations of the rising and falling limb of the hydrograph. For each streamgage, the minimum, most-probable value, and maximum ratios were calculated. Then the median of each of the three ratio values was taken from the three stations and used as inputs for the level-2 analysis.

The level-3 analysis was conducted in a similar manner to the level-2 analysis, except instead of using nearby streamgages with at least 5 years of record length, hydrographs from the Carter Creek USGS station 14348430 were used. This level-3 analysis is suboptimal for two reasons:

1. At the time of analysis, there were less than 2 years of streamflow data collected at station 14348430. Because of this short-term record, fewer hydrographs were available for comparison, and of the hydrographs selected, a higher percentage had less than ideal characteristics. When possible, hydrographs used for this analysis should have one smooth peak, little base flow before the event, and a clear start and end to the storm event.
2. No stage or streamflow data were collected at Wall Creek. Owing to the proximity and relatively similar drainage areas of Wall and Carter Creeks, these creeks presumably should have similar hydrograph shapes for any given storm. However, without the collection of stage data, it is not possible to confirm this presumption.

Estimation of Precipitation Statistics

In SELDM, the stormflow upstream from the intersection of interest is calculated in part using precipitation statistics. Synoptic storm event statistics are defined using the arithmetic mean value for seven parameters, and the coefficient of variation for five parameters (table 7).

Three approaches were used for estimating precipitation statistics. In the level-1 analysis, precipitation statistics were derived from the rain zone (Rain Zone 14). Rain zones defined in SELDM are geographically large (15 in the United States [Granato, 2010]). In comparison, ecoregions used to define some of the other hydrologic characteristics are substantially smaller (84 in the United States). Consequently, there can be substantial precipitation variability within any given rain zone, especially in locations that have high elevations and steep slopes such as the Siskiyou Pass.

For the level-2 analysis, precipitation statistics were taken from Risley and Granato (2014). The Risely and Granato analysis was roughly equivalent to a level-2 analysis that might be performed by any end-user, although their use of kriging may have resulted in better estimates than would a more conventional, level-2 analysis. Because the watersheds for Wall and Carter Creeks are in close geographic proximity, the precipitation statistics derived from the level-2 analysis are nearly identical.

For the level-3 analysis, the precipitation statistics from USGS station 420420122361500 (fig. 2) were derived in accordance with the methodology detailed by the U.S. Environmental Protection Agency (1992) using the period of November 7, 2017, to November 6, 2019. Data were compiled from several nearby National Oceanic and Atmospheric Administration (NOAA) weather stations. Rainfall patterns at the Medford precipitation gage (National Oceanic and Atmospheric Administration, 2019) were most similar to those at the USGS gage, so the Medford gage was chosen as an index gage.

Table 5. Upstream basin characteristics needed for Stochastic Empirical Loading and Dilution Model stormflow calculations.

[NA, not applicable]

Site characteristic	Units	Carter Creek—Branch 1			Wall Creek			Carter Creek—Branch 6
		Analysis Level 1	Analysis Level 2	Analysis Level 3	Analysis Level 1	Analysis Level 2	Analysis Level 3	Analysis Level 3
Hydraulics								
Drainage area	Square miles	0.246	0.246	0.246	0.91	0.91	0.91	0.58
Drainage length	Feet	2,531	2,531	2,531	8,042	8,042	8,042	2,531
Mean basin slope	Feet per mile	1,946.7	1,946.7	1,946.7	1,842.1	1,842.1	1,842.1	1,838.0
Impervious fraction	No units	0.07	0.07	0.07	0.011	0.011	0.011	0.0908
Basin development factor (BDF)	No units	–1	–1	1	–1	–1	2	1
Hydrograph recession								
Minimum	No units	1	NA	1.13	1	NA	1.13	1.13
Most probable value	No units	1.85	NA	2.42	1.85	NA	2.42	2.42
Maximum	No units	4.4	NA	4.41	4.4	NA	4.41	4.41

Table 6. Streamgages used for Stochastic Empirical Loading and Dilution Model level-2 analysis of hydrograph recession variables.

[MPV, most probable value; Or, Oregon]

Station number	Station name	Ratio of hydrograph rising limb to falling limb		
		Minimum	MPV	Maximum
14353000	West Fork Ashland Creek near Ashland, Or	1.13	2.13	4.41
14353500	East Fork Ashland Creek near Ashland, Or	1.05	2.42	3.48
14362250	Star Gulch Near Ruch, Or	1.55	3.25	7.45
	Mean	1.24	2.60	5.11
	Median	1.13	2.42	4.41

Table 7. Precipitation statistics used for Stochastic Empirical Loading and Dilution Model (SELDM) storm-event calculations.

[**Note:** Statistical term "mean" is used in this table, whereas "average" is used for SELDM inputs. COV, coefficient of variation; NA, not applicable]

Precipitation statistic	Analysis level							
	Level 1		Level 2		Level 3		Level 3	
	Rain zone		Carter Creek		Carter Creek		Wall Creek	
	Mean	COV	Mean	COV	Mean	COV	Mean	COV
Storm event volume, in inches	0.84	1.10	0.59	1.08	0.62	0.71	0.62	0.71
Storm event duration, in hours	12.0	0.92	10.7	0.91	14.0	0.83	14.0	0.83
Time between storm events, in hours	255	2.05	250	1.72	174	0.97	174	0.97
Minimum total storm volume, in inches	0.1	NA	0.1	NA	0.1	NA	0.1	NA
Minimum inter-event time, in hours	6.0	NA	6.0	NA	6.0	NA	6.0	NA
Number of storm events per year	35.0	0.340	35.98	0.280	49.74	0.44	49.74	0.44
Total volume of storm events per year, in inches	29.4	0.410	21.1	0.350	31.1	0.410	31.1	0.410

Precipitation statistics were calculated for both the NOAA Medford gage and USGS gage (420420122361500) from November 7, 2017, to November 6, 2019. The same statistics were calculated for the NOAA Medford gage for the entire period of record (January 1, 1950–December 21, 2019). Then, for each Medford precipitation statistic, the ratio between the entire period of record and the concurring record was calculated (table 8), and the USGS gage precipitation was adjusted according to the calculated ratio. For example, for the period in which the USGS gages and Medford gage were both active, the mean storm-event volume at the Medford precipitation gage was 0.25 inches. For the period of record, the mean storm event volume at Medford was 0.32 inches. The ratio of period of record mean storm event volume to concurring record storm event volume was 1.31 (mean storm event values are rounded in table 8; ratio adjustment is calculated using unrounded values). The mean storm event volume at the USGS gage was 0.48 inches. Multiplying that value by the ratio adjustment (1.31) results in a value of 0.62 inches (labeled as "USGS adjusted" in table 8), which represents the estimated mean storm event volume at the USGS gage for the period of record of the Medford gage (1950–2019).

Estimation of Streamflow Statistics

SELDM was designed to calculate prestorm streamflow volumes upstream from the highway-runoff mixing point as a stochastic variable. Nine streamflow statistics are needed for SELDM prestorm streamflow calculations (table 9).

Table 8. Adjustments made to Stochastic Empirical Loading and Dilution Model precipitation statistics based on Medford, Oregon, precipitation gage period of record statistics.

[CV, coefficient of variation; USGS, U.S. Geological Survey]

Precipitation gage	Mean storm event volume (inches)	CV storm event volume (inches)	Mean storm event duration (hours)	CV storm event duration (hours)	Mean time between storm events (hours)	CV time between storm events (hours)	Mean number of storm events	CV number of storm events (no units)
Medford, 2017–19	0.25	1.54	5.35	1.69	347.29	0.73	25.75	2.86
Medford, period of record	0.32	0.97	6.21	1.39	412.95	0.39	21.23	2.76
Percent (%) difference	−24%	59%	−14%	21%	−16%	86%	21%	4%
Adjustment	1.31	0.63	1.16	0.82	1.19	0.54	0.82	0.97
USGS	0.48	1.12	12.07	1.01	146.43	1.79	60.34	0.45
USGS adjusted	0.62	0.71	14.02	0.83	174.11	0.97	49.74	0.44

Table 9. Streamflow statistics used for Stochastic Empirical Loading and Dilution Model prestorm calculations.

Streamflow statistic	Statistic	Analysis level		
		Level 1	Level 2	Level 3
		Ecoregion	Nearby streams	Carter Creek tributary
Fraction of daily-mean streamflows recorded as zero flow	Decimal fraction	0.007	0	0
Arithmetic statistics for all daily mean streamflow values (in cubic feet per second per square mile)	Mean	2.270	0.506	0.416
	Standard deviation	4.107	2.603	0.490
	Skew	8.188	0.336	4.812
	Median	0.986	0.552	0.243
Retransformed log10 arithmetic statistics for nonzero daily mean streamflow values (retransfomed from cubic feet per second per square mile)	Mean	0.994	1.200	0.287
	Standard deviation	4.456	1.219	2.218
	Skew	0.332	5.049	0.746
	Median	0.994	0.552	0.243

Three approaches were used for estimating streamflow statistics. A level-1 analysis was used to generate streamflow statistics using the U.S. Environmental Protection Agency (EPA) Level III ecoregion of the Siskiyou Pass (Ecoregion 78: Klamath Mountains [U.S. Environmental Protection Agency, 2021b]). The approach used to estimate streamflow statistics by ecoregion is detailed in Granato (2010). The smallest drainage area of any watershed used in the Granato (2010) analysis was 10 mi^2, which is more than 1 order of magnitude larger than the drainage areas of the Carter Creek tributary (around 0.25 mi^2) or Wall Creek (0.91 mi^2). Only about 3 percent of streamgages monitored by the USGS in the past century have drainage areas less than 1 mi^2 (Granato and others, 2017). Consequently, the streamflow statistics derived from this level-1 analysis may not be hydrologically similar to flows in these small, high-altitude headwater basins. In cases such as these, where the assumption of hydrologic similarity between available statistics and local conditions may be in question, additional analyses may be required. In this case, analysis of streamflow data from smaller drainage areas would be needed to assess the representativeness of the level-1 analysis statistics.

The second approach used to estimate streamflow statistics was considered a level-2 analysis for this study and used nearby streamgages of similar drainage areas (table 10). Five nearby streamgages that have upstream drainage areas ranging from 8.14 to 168 mi^2 were chosen from the SELDM database for this analysis. Although these nearby streamgages are probably more hydrologically similar than streamgages within the larger ecoregion area, the similarity may be less than typical because the smallest drainage areas used for this analysis are about an order of magnitude higher than the larger of the two sites for which streamflow statistics are being estimated (Wall Creek).

Table 10. Streamgages used for Stochastic Empirical Loading and Dilution Model level-2 analysis of streamflow statistics.

[Table 10 (in the form of Microsoft Excel and .csv files) is available for download at https://doi.org./10.3133/sir20225091.]

For each streamflow statistic estimated, the median of all five streamgages was used in the analysis (table 10). Mean values were also calculated for each streamflow statistic to discern whether each distribution of values was skewed by outliers. The streamgages with larger drainage areas tended to have statistics that diverged from those with smaller drainage areas, so it was surmised that median values would more accurately represent conditions at Carter and Wall Creeks than the means of site statistics, given that both watersheds are small.

A third approach used to estimate streamflow statistics at the tributary to the Carter Creek site was considered a level-3 analysis but is a hybrid between a level-3 and level-2 analysis. In a level-3 analysis, streamflow data from a gaging station in operation for 10 years or more would be used to calculate the needed statistics. Because only 2 years of data were available for the tributary to Carter Creek site, an index site was used to augment the record at Carter Creek.

Five long-term streamgages were chosen as potential index sites for Carter Creek (table 11). For each streamgage, three regression models were created to estimate streamflow at the Carter Creek streamgage: (1) a linear regression model, (2) a linear-regression model in which all streamflow values were log10 transformed, and (3) a polynomial regression model. Each model was evaluated against measured streamflow at Carter Creek using three metrics: Nash-Sutcliffe efficiency, root mean squared error, and mean absolute error.

The Little River at Peel streamgage provided the best fit using all three metrics for each of the three regression models and was chosen for use in the analysis. Of the three regression models using the Little River streamgage data, the polynomial model resulted in the best goodness-of-fit metrics. However, the equation derived from the polynomial model resulted in decreases in estimated flow at Carter Creek with increasing flow at Little River for very high streamflow values. Consequently, the polynomial model was not used, and the linear model was chosen. The linear model goodness-of-fit metrics were generally second-best or close to second-best (depending on the metric) and resulted in a simple regression model with no possibility of negative streamflow values or streamflow values that decreased with increasing index station streamflow values.

The equation used to augment the Carter Creek streamgage time series of daily mean streamflow was:

$$Q_{CC} = 0.050 + {}^*Q_{LR} {}^* 0.000471, \quad (1)$$

where

Q_{CC} is the estimated daily mean streamflow in cubic feet per second at the Carter Creek tributary (Branch 6) at USGS station 14348430, and

Q_{LR} is the daily mean streamflow in cubic feet per second from USGS streamgage 14318000, Little River at Peel, OR.

The augmented record was analyzed using the USGS program QSTATS (Granato, 2009a, appendix 4), and the resulting statistics were used for analysis. The drainage area upstream from the I–5 crossing of the Carter Creek tributary represents 43.1 percent of the total drainage area upstream from USGS streamgage 14348430 (0.25 of 0.58 mi^2). Consequently, all calculated streamflow values at USGS streamgage 14348430 were multiplied by 0.431, and the resulting time series was again analyzed using QSTATS for all analyses taking place at the I–5 intersection with the Carter Creek Branch 1. Because no streamflow data were collected at Wall Creek, all streamflow statistics used for Carter Creek were also used to simulate streamflow at Wall Creek. Streamflow statistics are automatically scaled for drainage area because the statistics are entered as cubic feet per second per square mile.

Estimation of Volumetric Runoff Coefficient Statistics

Six volumetric runoff coefficient statistics are required for SELDM computations, three for the highway site and three for the upstream site (table 12). For the level-1 analysis, the default highway and upstream basin values included in SELDM were used. These values are taken from national studies (Granato and Cazenas, 2009; Granato, 2010; and Granato, 2013) and represent typical runoff characteristics based on the fraction of impervious area in the highway and upstream basin catchments. These national statistics were also used for SELDM scenarios that were conducted primarily as a level-2 analysis, as would be typical of such an analysis.

Table 11. Potential index sites for Carter Creek.

[NAD 83, North American Datum of 1983; NSE, Nash-Sutcliffe efficiency; RMSE, root mean squared error; MAE, mean absolute error; USGS, U.S. Geological Survey; Or, Oregon; blw, below]

USGS site identification	Site name	Latitude (NAD 83)	Longitude (NAD 83)	Drainage area (square miles)	Linear model			Log10-transformed linear model			Polynomial model		
					NSE	RMSE	MAE	NSE	RMSE	MAE	NSE	RMSE	MAE
14318000	Little River at Peel, Or	43.253	–123.026	177	0.55	0.25	0.14	0.60	0.34	0.28	0.60	0.23	0.14
14320934	Little Wolf Creek near Tyee, Or	43.431	–123.587	9.05	0.25	0.33	0.20	0.53	0.37	0.30	0.38	0.29	0.17
14353000	West Fork Ashland Creek near Ashland, Or	42.149	–122.717	10.7	0.28	0.32	0.20	0.42	0.41	0.33	0.26	0.32	0.19
14353500	East Fork Ashland Creek near Ashland, Or	42.153	–122.709	8.14	0.24	0.33	0.21	0.38	0.43	0.34	0.21	0.33	0.21
14354200	Bear Creek blw Ashland Creek at Ashland, Or	42.216	–122.722	168	0.48	0.27	0.16	0.28	0.46	0.35	0.56	0.24	0.17

Table 12. Volumetric runoff coefficients used for Stochastic Empirical Loading and Dilution Model storm-runoff calculations for the Siskiyou Pass, southern Oregon.

Analysis level	Example scenario number	Example scenario name	Volumetric runoff coefficient statistics	Highway			Upstream		
				Mean	Standard deviation	Coefficient of skewness	Mean	Standard deviation	Coefficient of skewness
1 and 2	2	CarterLvl2	National values	0.26	0.22	1.12	0.08	0.23	1.90
3	3	CarterLvl2VR3	Local values	0.19	0.27	1.95	0.14	0.14	1.48

A level-3 analysis was implemented by evaluating local study precipitation and streamflow data. For the highway site (420425122361700), individual storm events were determined using EPA standards commonly used to distinguish runoff-generating precipitation events: (1) a minimum interevent period of 6 hours and (2) a minimum event volume of 0.1 inch (U.S. Environmental Protection Agency, 1992). Highway and streamflow events were determined using the USGS Base-flow Estimation/Separation Tool (BEST; Smith, 2017). BEST was developed to identify storm events, to calculate EMCs for identified events, and to calculate flow and constituent concurrent runoff loads for a given watershed. Base-flow conditions are determined prior to an event, and flow and concentrations contributed by storm event runoff are then determined by increases and decreases in the hydrograph. Users define the requirements needed to trigger storm event computation based on the type of site (storm drain, continuous, or intermittent stream) and the magnitude of increase in the hydrograph. An additional seasonal adjustment factor is used to avoid higher base flow in the winter from being characterized as a single week-long event and to prevent small event-based fluctuations during low summer flows from being ignored. All parameters used for USGS stations 14348430 (Carter Creek Branch 6) and 420425122361700 (the intersection of Carter Creek Branch 1 and I–5) are shown in table 13. For streamflow upstream from USGS station 420425122361700, a drainage area ratio was used to compute streamflow inputs. In other words, each measurement of streamflow was multiplied by the ratio of the drainage area of USGS station 420425122361700 divided by the drainage area of USGS station 14348430.

A runoff event that began within a 3-hour window after a precipitation event was presumed to have originated from that precipitation event. Precipitation events that occurred between November and March were excluded from this analysis because such events may include melting snow, which may push volumetric runoff coefficients above one. Although this results in a smaller sample size for calculating runoff statistics, the censoring of winter precipitation events is not surmised to have a substantial influence on the calculated runoff statistics. To calculate volumetric runoff coefficients, for each series of linked events (precipitation-streamflow), the runoff volume (in cubic feet) was divided by the product of the precipitation (drainage area multiplied by total event precipitation, also in cubic feet). Volumetric runoff coefficients for highway runoff ranged from 0 to 0.79, with a mean, standard deviation, and skew values of 0.19, 0.27, and 1.95, respectively (table 12). These values are close to the level-one values of 0.26, 0.22, and 1.12 derived from national data (table 12). The lower mean volumetric runoff coefficient (relative to the national data) is surmised to result from the configuration of the highway site, in which runoff enters a ponded area and slows considerably, giving it a chance to infiltrate before reaching the tributary to Carter Creek.

A similar approach was taken with the upstream basin volumetric runoff coefficient statistics. However, the window between precipitation and streamflow events was widened to 24 hours to account for the time of travel between upstream precipitation and the streamgage as evidenced by the rising hydrograph. Volumetric runoff coefficients for the upstream basin ranged from 0 to 0.44, with mean, standard deviation, and skew values of 0.14, 0.14, and 1.48, respectively (table 12). These values are comparable to level-one values of 0.08, 0.23 and 1.90 derived from national data (table 12). The higher mean volumetric runoff coefficient in this study area probably resulted from the steep terrain and the presence of soils with low infiltration rates, allowing for less infiltration than in other watersheds.

Estimation of Water-Quality Statistics

Three methods are available in SELDM for simulating the water quality of runoff and receiving waters upstream from the sites of interest (Granato, 2013), and two are available for the highway catchment (site of interest). Upstream stormflow quality can be simulated as a random variable, a dependent variable, or a transport curve, which is a relation between streamflow and concentration. Runoff quality from the site of interest can be simulated as a random variable or as a dependent variable.

Table 13. Parameters used for computations with the Base-flow Estimation/Separation Tool for streams in the Siskiyou Pass, southern Oregon.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; NA, not applicable]

Parameter (units)	USGS station number	
	14348430	420425122361700
Type of station	Continuous flow	Intermittent flow
Type of data	Flow and water quality	Flow and water quality
Condition at start of record	Recession	Recession
Station drainage area (square miles)	0.58	0.014
Storm trigger (ft^3/s)	0.2	0.1
Storm trigger adjustment factor (dimensionless)	0.2	1
Peak trigger (ft^3/s)	NA	NA
Peak trigger ratio	0.5	1
Allowable missing data gap (hours)	2	2
Proportion of initial streamflow that is base flow	1	1
Initial base-flow water-quality multiplier	1	1
Stormflow recession adjustment factor	1	1

A level-1 water-quality analysis for highway-runoff concentrations would not be useful for the current study. An analyst must take care in simulating deicing-chemical concentrations because these constituents comprise two distinct populations (Risley and Granato, 2014). The first population, which is the result of atmospheric deposition, weathering of roadway and roadside materials, and other sources, may be simulated by using many of the datasets in the Highway-Runoff Database (Granato, 2019). The second population results from the application of massive amounts of deicing chemicals, which in turn results in concentrations in runoff that can be orders of magnitude higher than under normal conditions, such as periods when chloride deicers are not applied. Without deicing operations, sites may be selected on the basis of proximity to the ocean or the Great Salt Lake and local soil chemistry. However, many highway-runoff studies result in few if any samples per site from the seasons in which normal sampling is not confounded by the difficulties of sampling during winter conditions. Risley and Granato (2014) selected data from Massachusetts (Smith and Granato, 2010) to demonstrate the difficulty of simulating populations that can produce extreme values. However, the Massachusetts sites were close to the Atlantic Ocean, on a glacial terrain near sea level, and had a different climate from the mountainous, inland sites used in this study that have a warm-summer Mediterranean climate.

For the level-2 analysis, highway-runoff chloride concentrations were estimated from regional sites at a high enough elevation that samples might contain elevated levels of chloride from deicers. Site information and data were taken from the Highway-Runoff Database version 1.0.0b (Granato and others, 2018). Level-2 highway-runoff data were taken from the south summit of Lake Tahoe, California, which has similar geochemistry characteristics to the study area of the Siskiyou Pass (Rainwater, 1962). Chloride EMCs at Lake Tahoe ranged as high as 5,300 mg/L, suggesting the application of chloride deicer. EMCs were not available for magnesium or sodium and were not calculated as part of the level-2 analysis for this study. A list of highway sites used to estimate regional highway-runoff chloride concentrations and their EMC statistics can be found in table 14.

Because specific conductance data from the highway runoff were available (USGS station 420425122361700), specific conductance was modeled as a random variable, and chloride, sodium, and magnesium were modeled as variables dependent on specific conductance for the level-3 analysis. Because the values are simulated stochastically, the fit of the regression line is not as important as it would be if the values were simulated deterministically by using only values that fall on the regression line; the SELDM simulations re-create the variability in data above and below the regression line. Specific conductance EMCs were calculated using the BEST program, and the resulting concentration statistics for specific conductance were entered into SELDM as a random variable. Relations based on the observed values between specific conductance and chloride, sodium, and magnesium at the highway site were used for the highway dependent statistics (table 15).

For the upstream basin, a process similar to that used for the highway catchment was conducted. A typical level-1 analysis would have been inappropriate because base-flow concentrations of chloride, magnesium, and sodium differ greatly across regions of North America (Rainwater, 1962; Hem, 1992, Granato and others, 2015). For example, a study of magnesium levels in Canadian drinking water found that magnesium levels in “raw water” (water prior to treatment) ranged from 0.2 to 81.7 mg/L (Meranger and others, 1979).

Table 14. Highway sites near Lake Tahoe, California, used to estimate regional highway chloride event mean concentrations.

[CA SR, California State Route; EMC, event mean concentration; StDev, standard deviation; mg/L, milligrams per liter]

Site name	Dataset name	Samples	Average daily traffic	Impervious fraction	Mean chloride EMC (mg/L)	StDev chloride EMC (mg/L)	Skew chloride EMC (mg/L)
CA SR-267 Tahoe - 267N Brockway Summit	CALTRANS 2003 Highway Runoff Data	7	8,500	0.9	157	98.5	–0.16
CA SR-50 Tahoe - 50E Echo Summit South Lake Tahoe	CALTRANS 2003 Highway Runoff Data	27	11,600	0.8	460	1,095	3.72
CA SR-50 Tahoe - 50E Tahoe Airport South Lake Tahoe	CALTRANS 2003 Highway Runoff Data	38	14,100	1	435	710	2.11
CA SR-50 Tahoe - 50W Tahoe Meadows	CALTRANS 2003 Highway Runoff Data	17	37,000	1	630	928	2.59
CA SR-89 Tahoe - 89N D.L. Bliss State Park	CALTRANS 2003 Highway Runoff Data	13	3,000	0.9	241	253	1.85
	Total samples	102					

Table 15. Relation between specific conductance in microsiemens per centimeter and highway-runoff constituents at U.S. Geological Survey (USGS) stations 420425122361700, Highway Runoff Site near Interstate Route 5 and Old Highway 99; and 14348430, Unnamed Tributary to West Branch Carter Creek, near Ashland, Oregon.

[mg/L, milligrams per liter; USGS, U.S. Geological Survey]

Constituent	Intercept	Slope	Median absolute deviation of residuals (mg/L)	Minimum concentration (mg/L)	Maximum concentration (mg/L)	Number of concurrent samples
			USGS station 420425122361700			
Chloride	–0.919	1.1097	1.02	34.7	9,090	131
Magnesium	–1.784	1.0881	1.23	6.49	1,530	131
Sodium	–1.7646	1.2043	1.20	16	3,990	126
			USGS station 14348430			
Chloride	–1.1995	1.1812	1.07	94.3	1,190	22
Magnesium	–0.7739	0.7331	8.30	12.5	130	22
Sodium	–2.7943	1.5398	3.11	31.1	567	22

A level-2 analysis was conducted only for chloride because magnesium and sodium concentration data were not readily available, and chloride was the main water-quality constituent of concern for this study. Chloride concentration statistics were calculated using regional data. The surface-water quality data miner (Granato, 2009b) was used to find the five nearest USGS stations where five or more chloride samples have been collected (table 16). Chloride concentrations at these five stations ranged from 0.4 to 37 mg/L, with mean, standard deviation, and skew values of 4.79, 5.95, and 2.95, respectively (not shown).

A second, more representative (more local, but still regional in scope) level-2 analysis was constructed using the background data collected in the Bear Creek watershed for this study (see section, "Regional Background Concentrations of Chloride, Magnesium, and Sodium"). Chloride concentrations collected within the Bear Creek watershed ranged from 0.89 to 86 mg/L (fig. 6), with mean, standard deviation, and skew values of 14.8, 19.4, and 2.45, respectively (not shown). The mean and standard deviation statistics are substantially higher than those in the regional data, suggesting in this instance that use of regional data (largely from northern California) would result in a low estimate of upstream chloride concentrations.

For the level-3 analysis of upstream constituent concentrations, specific conductance was simulated using the "upstream random" option, and concentrations of chloride, magnesium, and sodium were simulated using the "upstream dependent" option. Statistics used for each of these simulations are shown in table 17. BEST was used to determine EMCs of specific conductance for each storm event, and the mean, standard deviation, and skew specific conductance values were calculated based on those events.

Discharge and specific conductance data from USGS stations 14348430 and 420425122361700 were used to determine the EMCs of specific conductance for a 2-year period beginning November 7, 2017. Data are not available for USGS station 420425122361700 until November 30, 2017; to fill in the missing period of the record, data values from November 7 to 30, 2018, were duplicated and inserted at the beginning of the record. BEST storm event output for each site was compared to its respective hydrograph as well as to precipitation data from USGS station 420420122361500 over several iterations to calibrate the output.

Maximum event mean values of specific conductance calculated by BEST for USGS stations 14348430 and 420425122361700 were 6,110 and 9,140 µS/cm, respectively. For comparison, published specific conductance values range from 50 to 1,500 µS/cm for potable water, are about 50,000 µS/cm for seawater, and are as much as 225,000 µS/cm for brines (Granato and Smith, 1999). Mean event-mean values of specific conductance calculated by BEST for USGS stations 14348430 and 420425122361700 were 1,030 and 1,500 µS/ cm, respectively.

SELDM Results

SELDM scenarios were run for Carter Creek Branch 1, Wall Creek, and Carter Creek Branch 6. The Carter Creek Branch 1 location represents a large highway catchment input into a small stream and can be thought of as a worst-case scenario for water-quality constituent event mean concentrations (EMCs), which are evaluated against the criterion maximum concentrations (CMCs). Because most of the hydrologic data were collected for Carter Creek Branch 1, level-3 estimates should be more representative of true conditions than at other locations. Carter Creek Branch 6 represents conditions downstream from multiple confluences of Carter Creek and assumes similar inputs per unit area for all branches. Wall Creek is a neighboring watershed, which has lower levels of chloride deicer application relative to Carter Creek, and accordingly where fewer data were collected for analysis.

Sensitivity analyses were performed for the Carter Creek Branch 1 site to evaluate the leverage of selected input variables. SELDM results were also compared with measured values from the highway runoff at Carter Creek Branch 1 and with stream EMCs at Carter Creek Branch 6 and Wall Creek. Finally, both simulated and measured results were compared with annual highway loads of chloride deicers as reported by ODOT. Note that SELDM simulates the concurrent highway-runoff, upstream, and downstream loads. The highway contributes to total annual loads only during events when runoff from the highway is discharging to the stream. The upstream basin, however, discharges during the entire year if it is a perennial stream, during wet seasons if it is an intermittent stream, and during runoff events if it is an ephemeral stream. Simulated loads described in this section are for concurrent runoff periods when highway runoff is discharging to the stream. If total annual upstream loads are required, a SELDM user could use the lake package to derive upstream loads for the entire multiyear flow periods or other tools, like LOADEST (Runkel and others (2004).

Table 16. U.S. Geological Survey stations used to calculate regional concentrations of chloride, California and Oregon.

[USGS, U.S. Geological Survey; mi², square miles; mg/L, milligrams per liter; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NA, not applicable; R, River; nr, near; Ca, California; Br, Branch; S., South]

Site number	USGS station name	Latitude	Longitude	Horizontal datum	Altitude of gage (feet)	Altitude datum	Drainage area (mi²)	Chloride sample concentrations			Count
								Minimum (mg/L)	Mean (mg/L)	Maximum (mg/L)	
11517500	Shasta R nr Yreka Ca	41.82292	–122.596	NAD 83	2,000	NGVD 29	793	8.7	20.3	37.0	17
11519500	Scott R Nr Fort Jones Ca	41.64069	–123.015	NAD 83	2,623.8	NGVD 29	653	0.4	3.1	7.3	19
11532500	Smith R Nr Crescent City Ca	41.7915	–124.076	NAD 83	79.26	NGVD 29	614	1	2.5	12	111
11532626	Mill C A Br Nr Crescent City Ca	41.77428	–124.1	NAD 83	Unknown	NA	35.1	2.5	3.7	4.5	6
14308600	S. Umpqua River at Days Creek, Or	42.96734	–123.168	NAD 83	738.55	NGVD 29	641	1.1	5.8	13	29

Table 17. Water-quality constituent statistics used in Stochastic Empirical Loading and Dilution Model analyses of selected streams in the Siskiyou Pass, southern Oregon.

[Table 17 (in the form of Microsoft Excel and .csv files) is available for download at https://doi.org./10.3133/sir20225091.]

Carter Creek, Branch 1

Because most of the hydrologic data were collected for Branch 1 of Carter Creek, most of the SELDM scenarios focused on this location. SELDM scenario 1, designated “CarterLvl1,” is a level-1 analysis of the intersection of Carter Creek Branch 1 and I–5. This is a planning-level analysis, in which default national or regional data were used to estimate the statistical input parameters at the location.

Results from CarterLvl1 indicated that the mean of the EMCs of chloride from highway runoff (696 mg/L) was more than two orders of magnitude higher than the mean of the upstream EMCs (4.74 mg/L, fig. 8). Mixing resulted in a mean downstream EMC of 98.7 mg/L, which is a substantial increase from upstream levels. Median EMCs were substantially lower than mean EMCs for all three locations (upstream, highway, and downstream) because of the high level of skewness of the population of EMCs. Median values were about an order of magnitude lower than mean values for highway and downstream EMCs of chloride and about one-half of mean EMCs of chloride upstream. The ratio of mean to median values was smaller upstream relative to downstream and from the highway because the high levels of chloride application at high elevation sites during winter storms resulted in substantially higher EMCs for the highway and downstream locations. Conversely, upstream EMCs of chloride were driven by natural processes, so the ratio of mean to median EMCs was much lower.

SELDM scenario 2, designated “CarterLvl2” in figure 8, is a level-2 analysis of the same highway-creek intersection as CarterLvl1. This type of analysis uses regional data and statistics and requires substantially more effort that a level-1 analysis because regional data must be compiled and analyzed.

Results from CarterLvl2 were similar to those in scenario 1 (CarterLvl1), and, in general, resultant EMC differences between CarterLvl1 and CarterLvl2 were less than the uncertainty in the model inputs. The mean of the highway EMCs (682 mg/L) was more than 2 orders of magnitude higher than the mean of the upstream EMCs (4.96 mg/L, fig. 8), and mean of the downstream EMCs (52.6 mg/L) was more than 1 order of magnitude higher than the mean of the upstream EMCs. Mean downstream chloride EMCs were substantially higher because of the application of road deicers, although the increase was less than the estimates derived from the level-1 analysis (CarterLvl1). Median downstream EMCs of chloride were about an order of magnitude lower than mean downstream EMCs because of the high level of skewness in the population of EMCs, as in CarterLvl1. The median of upstream EMCs of chloride was closer to the mean and plot as a smaller boxplot, indicating less variability and less skewness.

For ease of comprehension, the next scenario discussed will be scenario 11. Scenarios 3–10 will be discussed in subsequent sections. SELDM scenario 11, designated “CarterLvl3” in figure 8, is a level-3 analysis of the same intersection of Carter Creek Branch 1 with I–5. This type of analysis is conducted using as much local data as possible and is generally considered the best representation of current conditions. Results from scenario 11 indicate much less variability in EMCs of chloride than was observed in the level-1 or level-2 analyses, especially for highway runoff. This is a result of using local rather than regional data. Regional data can be from a wide variety of hydrologic conditions, chloride application rates, and background chloride levels upstream. Such variability in conditions may result in regional-data statistics with high or extreme outliers that result in a large coefficient of skewness for the population. The high or extreme outliers caused mean EMCs to be much higher than median values, which is evident in the highway-runoff EMCs of chloride for CarterLvl1 and CarterLvl2. For both of those scenarios, the mean values were more than 1 order of magnitude greater than the median highway-runoff EMC of chloride. CarterLvl3 primarily used local data from a single location, which resulted in less variability and less skew of the population of EMCs of chloride (fig. 8).

The CarterLvl3 mean of highway-runoff EMCs of chloride (484 mg/L) was lower than the means in the previous two scenarios (696 and 682 mg/L), but the median value of CarterLvl3 (292 mg/L) was substantially higher than those of CarterLvl1 and CarterLvl2 (67.3 and 54.3 mg/L, respectively). The mean of the downstream chloride EMCs in CarterLvl3 were lower than in CarterLvl1 and similar to that in CarterLvl2. The discrepancy between CarterLvl1 and the other two scenarios (CarterLvl2 and CarterLvl3) is also apparent in the ratio of downstream to upstream mean chloride EMCs (table 18). The results from this simulation show that the application of road deicer increased downstream chloride EMCs for all scenarios, but both level-2 and level-3 analyses indicate that a smaller proportion of the chloride is from highway runoff than a level-1 analysis would suggest. Similar results were found for sodium and magnesium.

The upstream, highway-runoff, and downstream constituent EMCs of sodium had similar patterns to level-1, level-2, and level-3 analyses of chloride (scenarios 1, 2, and 11, respectively). Mean highway EMCs of sodium were about an order of magnitude higher than mean upstream EMCs and mean downstream sodium EMCs were between upstream and highway EMCs (fig. 9). Highway median EMCs of sodium were generally about one-half the value of mean EMCs, indicating substantial skew in the population of sodium EMCs but less skew than was present with chloride. Variability in the EMCs of sodium for upstream and downstream flow was less than for highway runoff for all three scenarios.

Downstream mean EMCs of sodium ranged from about 24 to 36 mg/L (fig. 9), with the level-1 analysis (CarterLvl1) producing the highest mean downstream EMC value. Median downstream EMCs of sodium ranged from about 18 to 21 mg/L. Highway and upstream mean EMCs of sodium varied little between the three levels of analysis. Consequently, the difference between the downstream sodium EMCs for the three levels of analysis were primarily driven by the variation of upstream flow (fig. 10) and highway runoff (fig. 11).

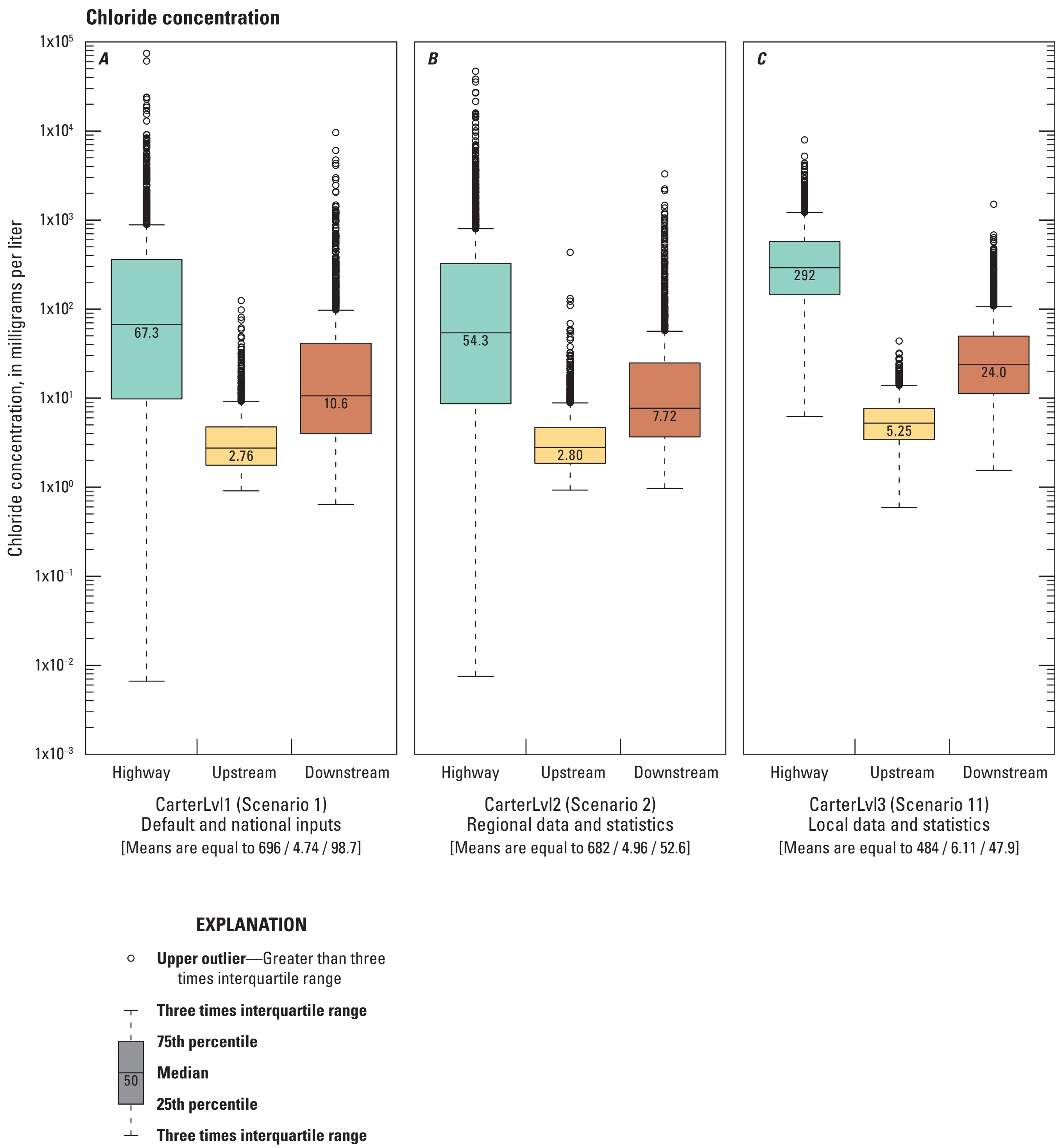


Figure 8. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 1 (CarterLvl1), (*B*) 2 (CarterLvl2), and (*C*) 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Table 18. Comparison of Stochastic Empirical Loading and Dilution Model (SELDM) chloride and magnesium outputs from scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) for the Siskiyou Pass, southern Oregon.

[mg/L, milligram per liter; ft^3, cubic feet]

SELDM scenario	Scenario abbreviation	Mean of chloride event mean concentrations			Ratio of downstream/ upstream chloride concen- tration	Mean of magnesium event mean concentrations			Ratio of downstream/ upstream magnesium concen- tration
		Highway (mg/L)	Upstream (mg/L)	Down- stream (mg/L)		Highway (mg/L)	Upstream (mg/L)	Down- stream (mg/L)	
1	CarterLvl1	696	4.74	98.7	20.8	57	9.12	17.1	1.9
2	CarterLvl2	682	4.96	52.6	10.6	57	9.12	12.9	1.4
11	CarterLvl3	484	6.11	47.9	7.8	57.1	9.13	13.3	1.5

Similar patterns to those for chloride and sodium were apparent in the level-1, level-2, and level-3 analyses for EMCs of magnesium (fig. 12). Mean and median highway and upstream EMCs of magnesium were consistent between all three analyses. Mean and median downstream EMCs of magnesium were more variable than upstream or highway EMCs. This increased variability was, once again, caused by the differences between upstream and highway-runoff flows, which resulted in a different proportion of highway runoff downstream. For all three scenarios, highway median EMCs of magnesium were about 60 percent of mean EMCs owing to moderate levels of skewness in the population. Conversely, mean upstream EMCs were nearly identical to median upstream EMCs owing to low levels of skewness.

Results of the three scenarios indicate that a level-1 analysis (CarterLvl1, national data) tends to produce larger mean downstream EMCs for all three water-quality constituents compared to level-2 or level-3 analyses (CarterLvl2 [regional data] and CarterLvl3 [local data], respectively). These differences are in part owing to differences in upstream flow (fig. 10), highway runoff (fig. 11), and the ratio between the two flows (table 19). With a smaller ratio of upstream flow to highway runoff, the percentage of downstream flow derived from the highway runoff is greater, and the mean highway-runoff EMCs of chloride were consistently about two orders of magnitude higher than upstream EMCs of chloride. Because scenario CarterLvl1 has a smaller upstream streamflow to highway runoff ratio than CarterLvl2 and CarterLvl3, the concentration of highway-runoff chloride is diluted less than in the other two scenarios, resulting in larger downstream EMCs of chloride.

Although level-3 simulations are presumed to provide more accurate results and more certainty about the applicability of SELDM for Carter Creek Branch 1, the uncertainties inherent in the measurements used to calculate the statistical inputs for SELDM are greater than the differences observed between the three levels of simulations. For example, Harmel and others (2006) found that, averaged across all constituents, calculated cumulative probable uncertainties for typical small watersheds ranged from 6 to 19 percent for streamflow measurements, from 4 to 48 percent for sampling collection, and from 5 to 21 percent for laboratory analysis. Although there is considerable uncertainty in measured and simulated concentrations and flows to represent long-term conditions, the differences in concurrent runoff loads between the three scenarios considered in this study are larger than the measurement uncertainty of individual concentration and flow measurements quantified in Harmel and others (2006).

This difference in downstream EMCs between the three scenarios affects estimated annual concurrent runoff loads of chloride downstream from the intersection (fig. 13). Compared to scenarios CarterLvl1 and CarterLvl2, CarterLvl3 produced the least amount of variability between individual years of simulated chloride runoff, as is evidenced by the smaller slope of points from CarterLvl3 in figure 13. CarterLvl1 estimated the largest median annual concurrent runoff loading of chloride (8,700 pounds), largely owing to having a larger typical highway-runoff volume than scenarios CarterLvl2 and CarterLvl3 (fig. 13). Conversely, CarterLvl2 estimated the smallest median annual concurrent runoff loading of chloride (5,100 pounds), largely owing to having the lowest highway EMCs of chloride (fig. 8).

The annual concurrent runoff loading of sodium for scenarios CarterLvl1, CarterLvl2, and CarterLvl3 did not have the same characteristics as that of chloride. CarterLvl1 (level-1 analysis) and CarterLvl3 (level-3 analysis) estimated similar median annual concurrent runoff loads of sodium, with CarterLvl1 being larger (fig. 14). CarterLvl2 resulted in a median annual concurrent runoff load of sodium that was 29–35 percent lower than the other two scenarios. This lower median annual concurrent runoff load of sodium was in part owing to CarterLvl2 having the lowest median downstream EMCs of sodium, but also in part to having the second-lowest median highway runoff (fig. 11). The slope in figure 14 is similar for all three scenarios, indicating consistent variability.

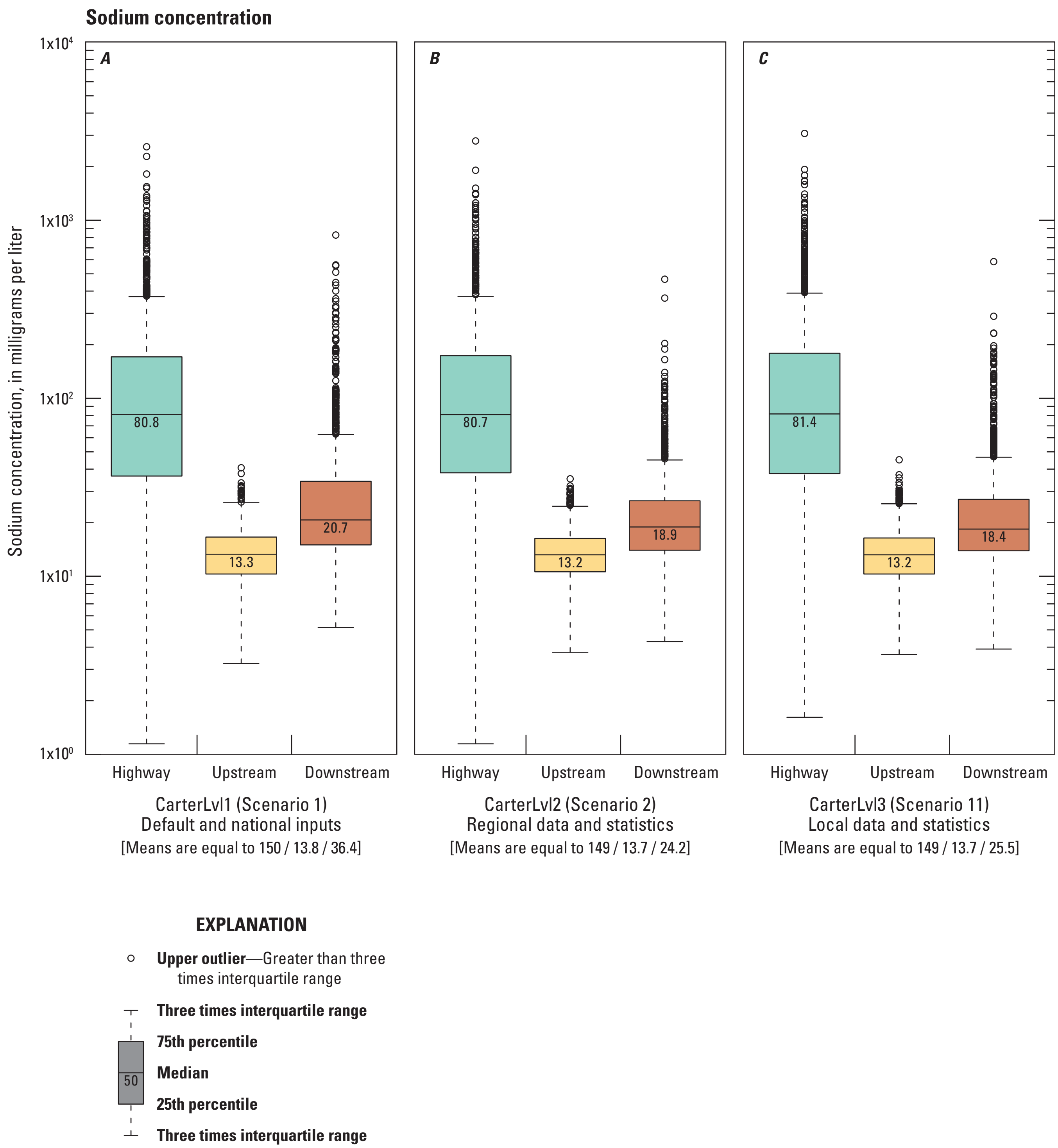


Figure 9. Highway-runoff, upstream, and downstream event mean concentrations of sodium for scenarios *(A)* 1 (CarterLvl1), *(B)* 2 (CarterLvl2), and *(C)* 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

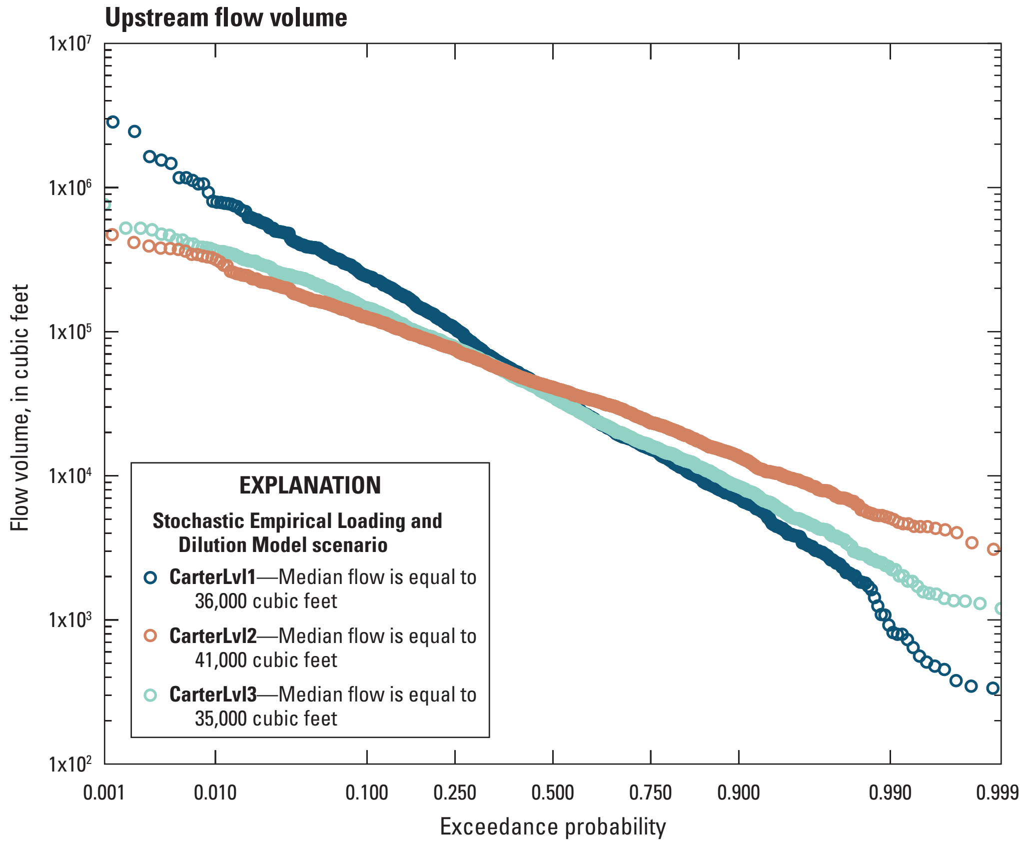


Figure 10. Exceedance probabilities of stormflow volumes under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

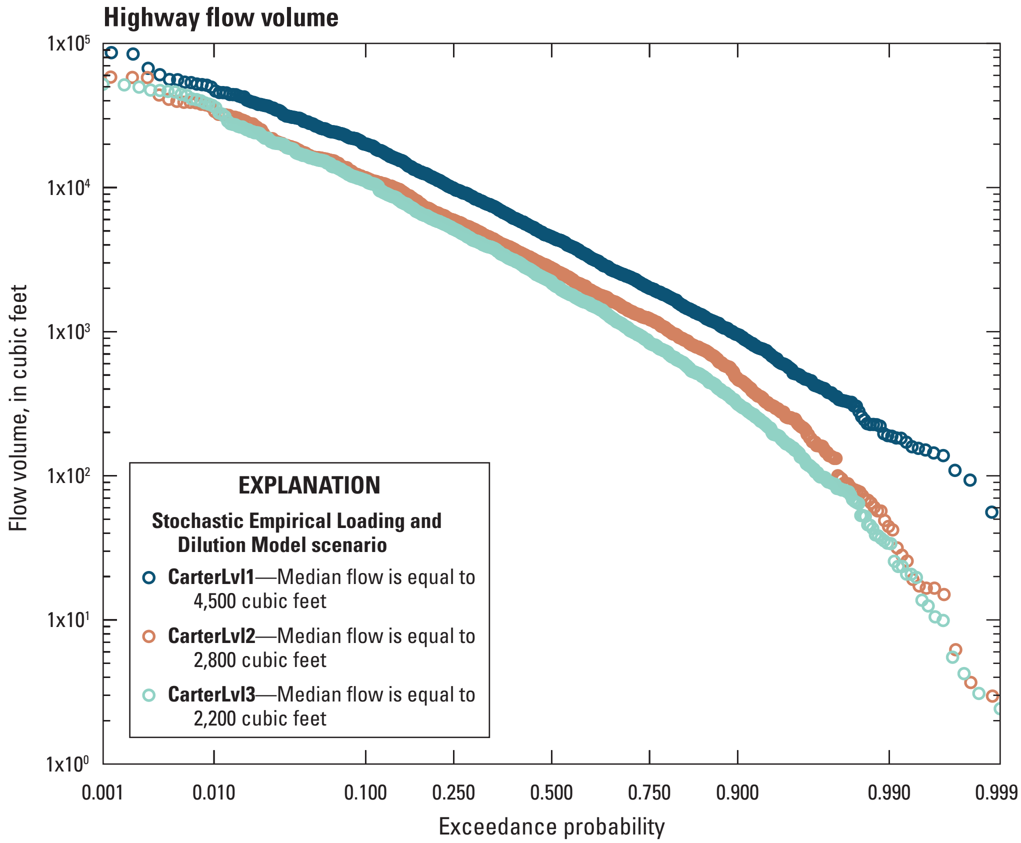


Figure 11. Exceedance probabilities of highway-runoff volumes under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

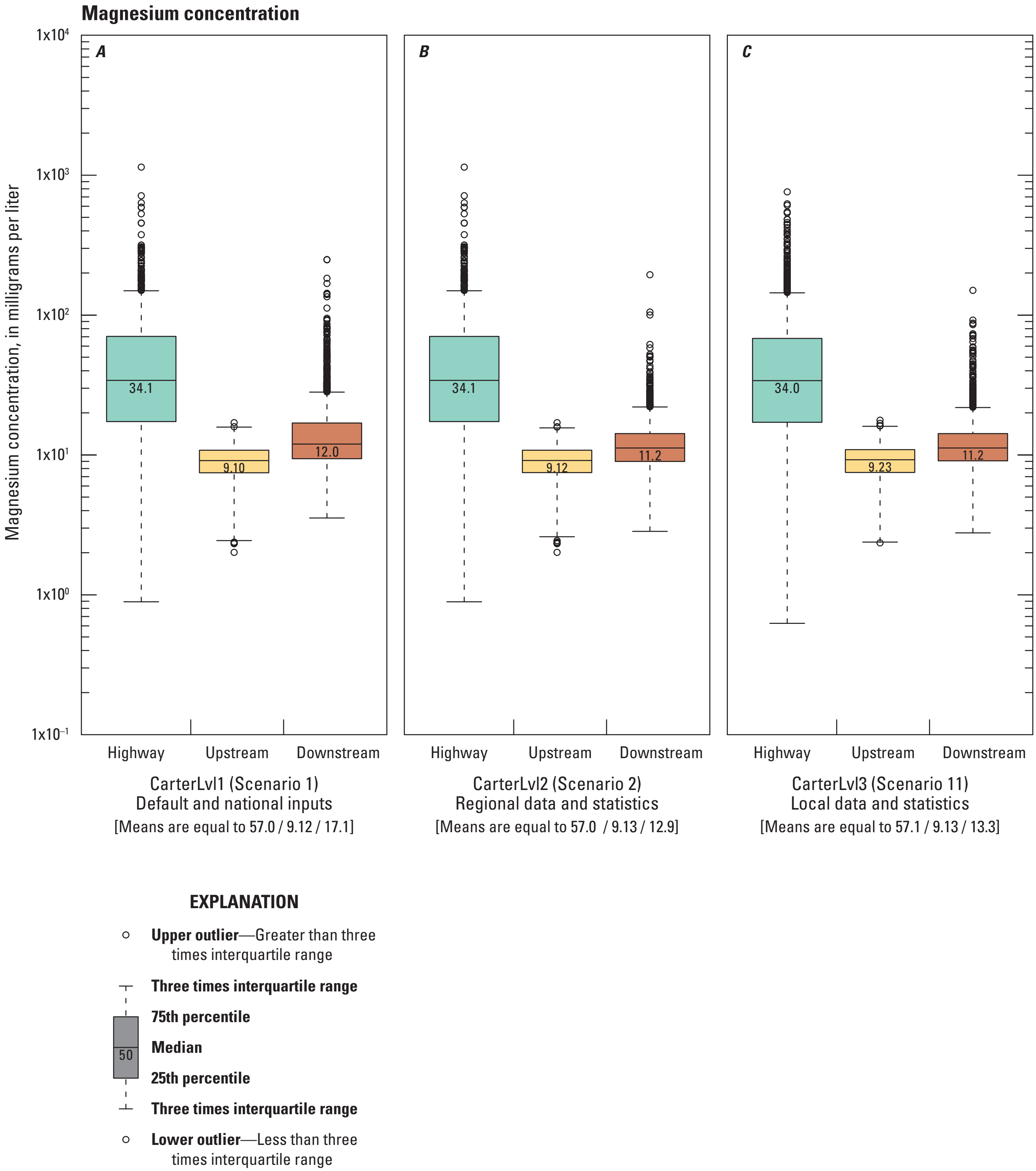


Figure 12. Highway-runoff, upstream, and downstream event mean concentrations of magnesium for scenarios (*A*) 1 (CarterLvl1), (*B*) 2 (CarterLvl2), and (*C*) 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Table 19. Comparison of Stochastic Empirical Loading and Dilution Model (SELDM) sodium and ratio outputs from scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) for the Siskiyou Pass, southern Oregon.

[mg/L, milligram per liter; ft³, cubic feet]

SELDM scenario	Scenario abbreviation	Mean of sodium event mean concentrations			Ratio of downstream/ upstream sodium concentration	Median upstream streamflow (ft³)	Median highway runoff (ft³)	Ratio of median upstream/ median highway runoff
		Highway (mg/L)	Upstream (mg/L)	Downstream (mg/L)				
1	CarterLvl1	150	13.8	36.4	2.6	36,000	4,500	8
2	CarterLvl2	149	13.7	24.2	1.8	41,000	2,800	14.6
11	CarterLvl3	149	13.7	25.5	1.9	35,000	2,200	15.9

The annual concurrent runoff loading of magnesium shows a similar pattern to that of sodium, with CarterLvl1 having the largest median annual concurrent runoff load of magnesium (2,700 pounds) and CarterLvl2 having the smallest median (1,700 pounds; fig. 15). Median downstream EMCs of magnesium were similar for all three scenarios, so the annual difference was primarily driven by the difference in highway runoff and upstream flow. The slopes in figure 15 are larger than those in figure 14, suggesting relatively greater variability in annual concurrent runoff loading from low to high exceedance probabilities than was observed for sodium.

Because load calculations are multiplicative, the combination of higher flows and higher concentrations results in storm loads that are much greater in size relative to typical conditions (median values) than what is seen for flows or concentrations individually. Consequently, for all three water-quality constituents, the storm events with the lowest probability of exceedance of concurrent runoff load (in other words, the events with the highest loads) represent a disproportionate amount of the total annual concurrent runoff load from storm events. This disproportionality can be observed in table 20, which shows the percentage of annual concurrent runoff load from storm events that can be attributed to the largest 1 and 10 percent of storm events by load for each of the three water-quality constituents in CarterLvl3. In other words, table 20 shows how much of the annual concurrent runoff load of a given constituent travels downstream for the largest 1 or 10 percent of events, divided by the same annual concurrent runoff load of all events. This disproportionality is another way of analyzing the effects of the skewness values of the population on annual load. Populations with large values of positive skew and (or) high variability (standard deviation) typically have greater degrees of disproportionality. Conversely, a population with zero standard deviation and zero skewness would have no disproportionality, such that the top 10 percent of events would account for exactly 10 percent of the total annual concurrent runoff load.

Table 20 shows that the degree of disproportionality among each of the three water-quality constituents is similar. Chloride has the highest disproportionality of the three constituents, which may be a result of being an ingredient in both deicer solutions (NaCl and $MgCl_2$). Because chloride is applied to the road in any deicing effort, the constituent will deviate from baseline conditions more frequently than magnesium or sodium, which may be applied sparingly or not at all for any given event. The difference in the degree of disproportionality may affect any prescribed mitigation efforts. For a constituent with a higher degree of disproportionality, a large percentage of that constituent's transport would occur at large events, and remediation efforts could be made to target only such events. Conversely, if a constituent had no disproportionality, it would occur in equal loads for every event, and a different approach might be needed for mitigation.

Another approach to evaluating SELDM scenarios is to analyze the percentage of storm events that exceed a given CMC. For chloride, CarterLvl1, CarterLvl2, and CarterLvl3, the ODEQ acute water-quality criterion value of 860 mg/L (fig. 16) was used as a CMC. The black, horizontal dotted line on figure 16 represents that CMC. For SELDM scenarios CarterLvl1, CarterLvl2, and CarterLvl3, downstream EMCs of chloride exceeded this CMC 2.3, 1.0, and 0.06 percent of the time, respectively[1]. The target exceedance (the dotted, vertical line) in figure 16 shows the probability at which there is a 1 in 3 chance of the EMC from at least one storm exceeding this CMC in a given year. Based on the mean number of storm events per year, this equates to an exceedance probability of 1.19 percent (table 21). This metric was based on the National Pollutant Discharge Elimination System (NPDES) definition of biologically based flow (U.S. Environmental Protection Agency, 2019). If the target exceedance line is to the right of the intersection of the EMC data and the line representing the constituent concentration criterion, the estimated frequency is lower than a 3-year return interval, and the model results indicate that the hypothetical water-quality criterion will be met (water quality would be better than the given criterion).

[1]For all probability plots, exceedance probabilities range from 0.001 (0.1 percent) to 0.999 (99.9 percent). In scenario 11 (CarterLvl3), one of the 1606 simulated EMCs was above the CMC of 860 mg/L of chloride and does not appear on figure 16 (a larger range of probability values would be needed to view all results). Figure 16 was not replotted with a greater range of exceedances to maintain consistency with other figures.

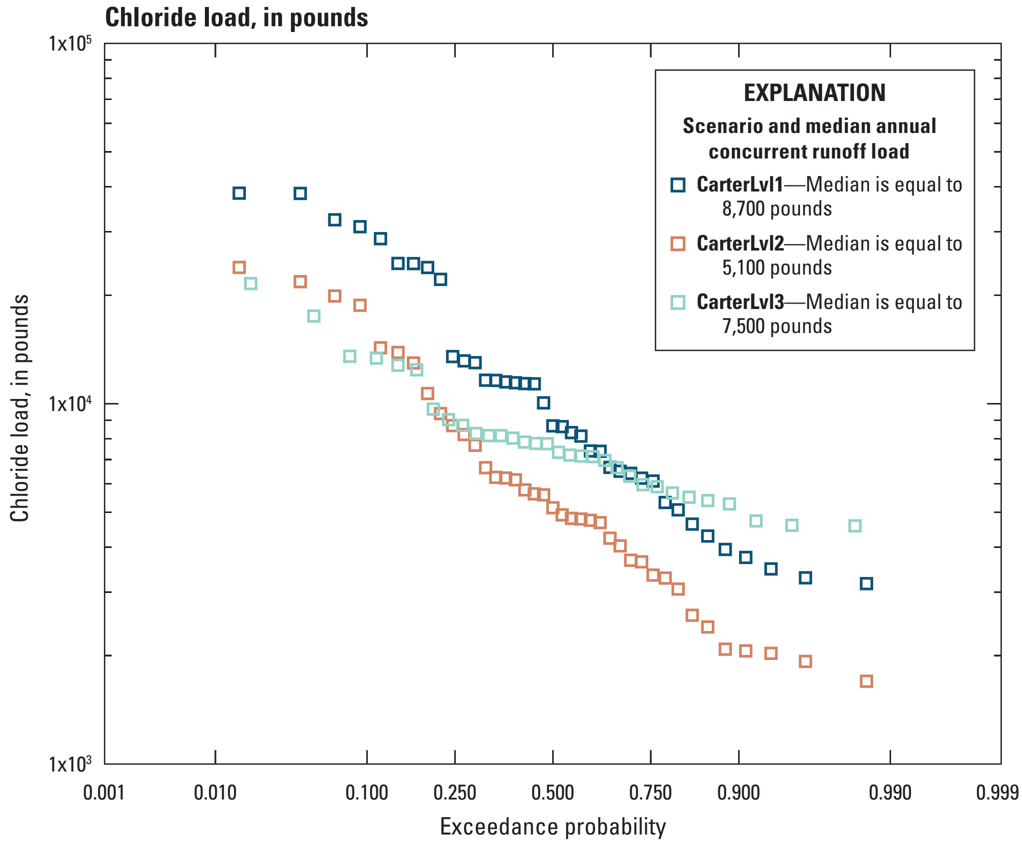


Figure 13. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

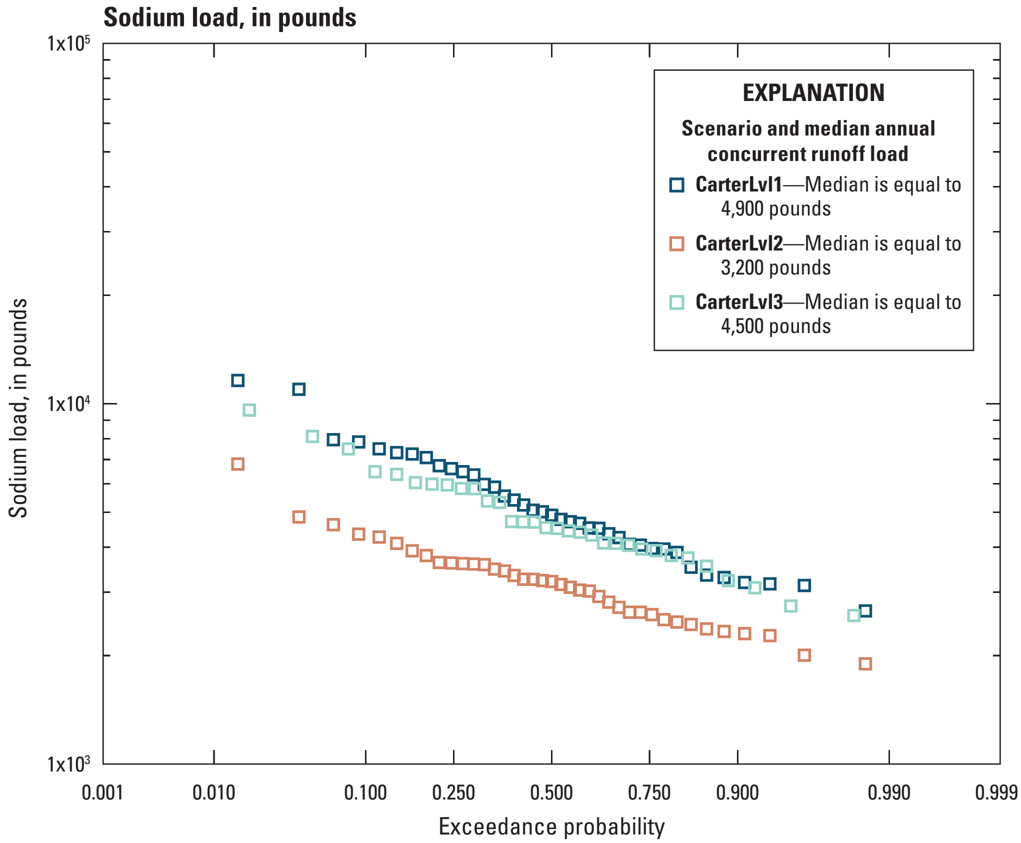


Figure 14. Exceedance probabilities of annual concurrent runoff loads of sodium under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

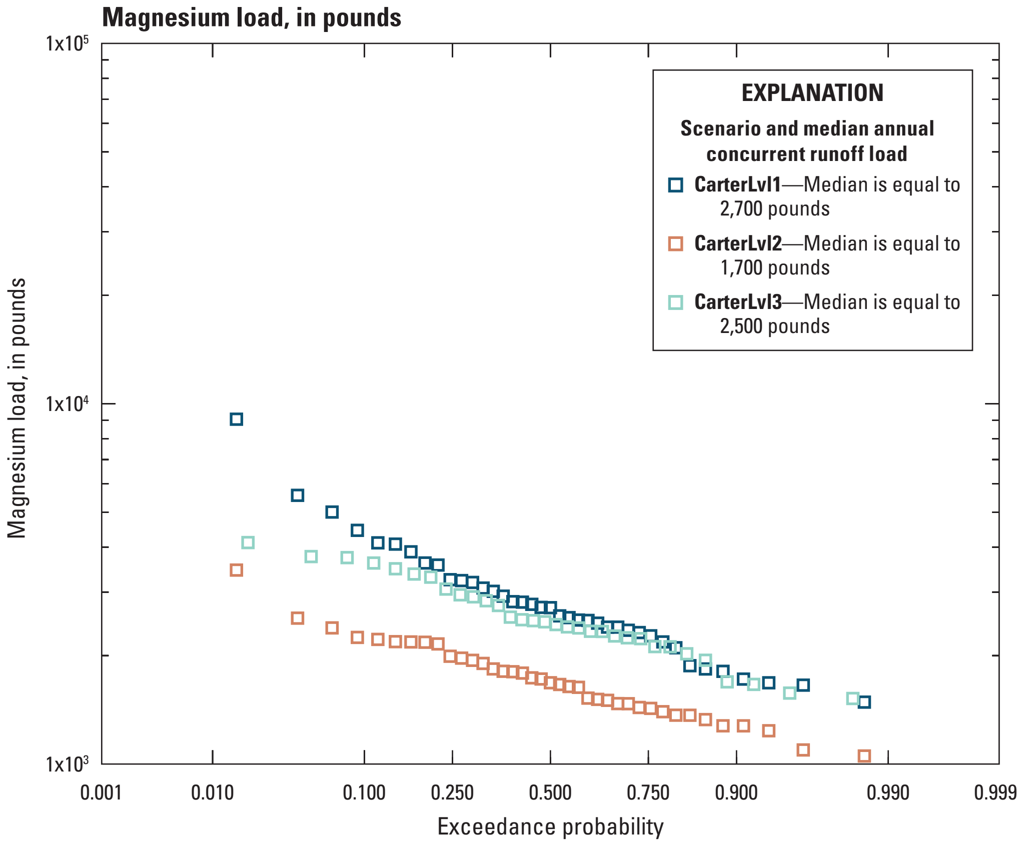


Figure 15. Exceedance probabilities of annual concurrent runoff loads of magnesium under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Table 20. Percentage of annual concurrent runoff load represented by the largest 1 and 10 percent of storm events by load for simulation 11 (CarterLvl3), Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Water-quality constituent	Percentage of total annual load	
	Largest 10 percent of events (percent)	Largest 1 percent of events (percent)
Chloride	58.0	23.9
Magnesium	42.8	12.2
Sodium	47.4	16.5

On the basis of the NPDES metric, the level-1 analysis suggests that the target criterion would not be met (fig. 16). For level-2 and level-3 analyses, only 1.0 and 0.06 percent, respectively, of EMCs exceed the ODEQ acute water-quality criterion for chloride, which is below the target criterion of 1.19 percent. Although few of the CarterLvl3 EMCs exceeded the CMC for chloride, the downstream EMCs in this scenario were higher than downstream EMCs in the other scenarios in about 75 percent of events (the high-frequency low-flow events). The CarterLvl3 concentrations were higher at these exceedance probabilities because the background EMCs were higher in this scenario.

An identical analysis was performed for sodium (fig. 17) and magnesium (fig. 18). For sodium, a CMC of 30 mg/L was chosen based on EPA recommendations for drinking water (U.S. Environmental Protection Agency, 2003). Figure 17 shows that about 1 in 5 downstream EMCs exceeded this CMC based on the level-3 analysis. The results also show little difference for downstream sodium EMCs between simulations for all three scenarios at high exceedance probabilities (at low concentrations; right side of figure), but substantial difference at low exceedance probabilities (at high concentrations; left side of figure). CarterLvl2 had the lowest rate of CMC exceedance and CarterLvl1 had the highest, but none of the three scenarios meet the target rate of 1.19-percent.

Magnesium is generally associated with health benefits (World Health Organization, 2020), although excess magnesium will increase the hardness of water, which may have negative effects on industrial infrastructure such as boilers or cooling towers, or the formation of limescale in water heaters. No drinking water standard or other environmental criteria were found for magnesium as part of this study. For the purposes of this study, an arbitrary

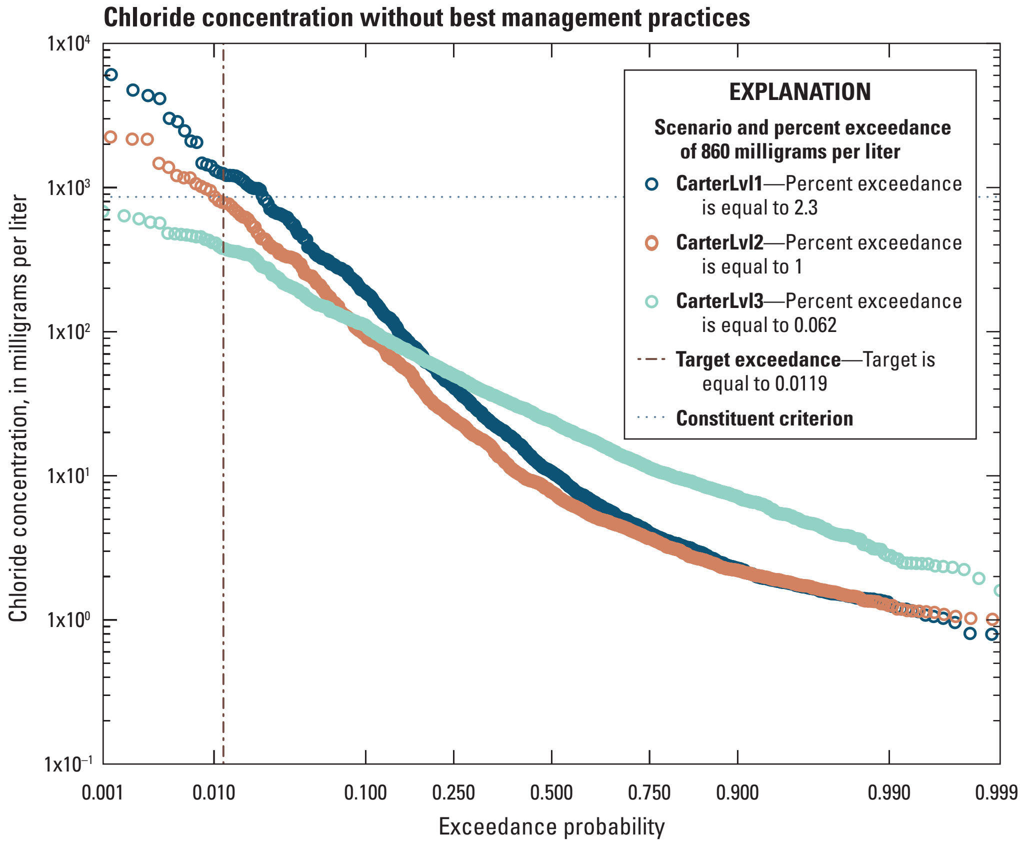


Figure 16. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

CMC of 100 mg/L was chosen for illustrative purposes. That concentration is in the range defined as "moderately hard" (U.S. Geological Survey, 2018b).

Figure 18 shows similar patterns in magnesium EMCs to those of sodium. EMCs were consistent between all three scenarios at high exceedance probabilities (at low concentrations; right side of figure) and diverge substantially at low exceedance probabilities (at high concentrations; left side of figure). The results also show that a level-1 analysis would lead to an overestimation of CMC exceedance rates relative to the level-3 analysis, although all three scenarios indicate the study magnesium criterion would be met.

Exceedance probabilities of the water-quality CMCs can also be evaluated by comparing upstream and downstream EMCs. Figure 19 shows the exceedance probabilities for upstream and downstream chloride EMCs for CarterLvl3, the level-3 analysis. The results show an increase in chloride EMCs for all exceedance probabilities, with the largest increases occurring at the lowest exceedance probabilities. The results also show that the highest upstream chloride EMCs were more than 1 order of magnitude lower than the study water-quality CMC for chloride. For example, at the target exceedance probability of 1.19-percent, upstream chloride EMCs are about 21 mg/L, which is more than 2 orders of magnitude below the chloride CMC of 860 mg/L.

The increase in EMCs between upstream and downstream from the I–5 crossing for sodium has a similar pattern to that of chloride (fig. 20). At high exceedance probabilities, the EMCs are close and have nearly the same slope. At lower exceedance probabilities the downstream EMCs increase at a much faster rate than the upstream EMCs, which could be the result of instances in which large volumes of NaCl were applied to the road. The rate of exceedance of the EPA 30-mg/L sodium CMC was substantially less for upstream than downstream EMCs. CarterLvl3 results suggest exceedances of this CMC will still occur in about 1 percent of upstream EMCs and about 25 percent of downstream EMCs.

The results of CarterLvl3 for magnesium show a similar pattern to that for sodium (fig. 21). EMCs of magnesium were similar at high exceedance probabilities, and the highest divergences in EMCs occurred at low exceedance probabilities.

Table 21. Allowable exceedance probabilities for Stochastic Empirical Loading and Dilution Model scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) for Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Scenario	Scenario name	Number of storms	Number of years	Storms per year	Percentage allowable
1	CarterLvl1	1,322	39	33.9	0.98
2	CarterLvl2	1,343	39	34.4	0.97
11	CarterLvl3	994	63	15.8	2.11
Mean		1,220	47	28	1.19

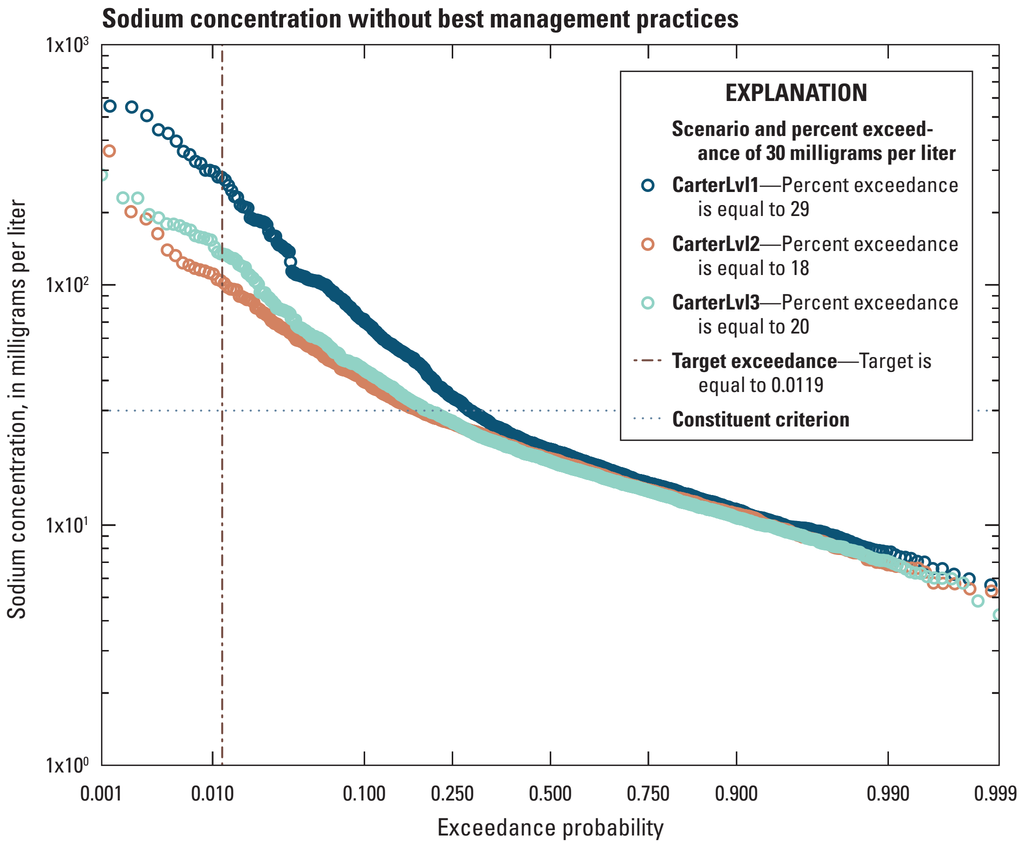


Figure 17. Exceedance probabilities of downstream event-mean concentrations of sodium under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

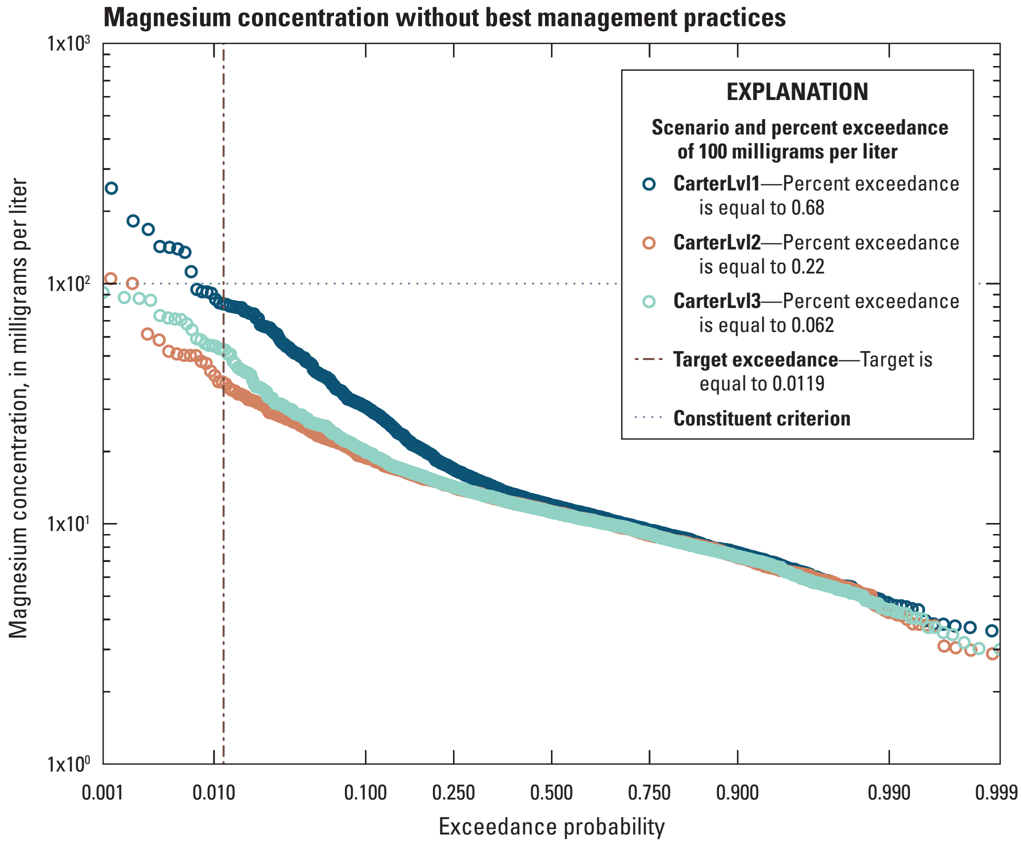


Figure 18. Exceedance probabilities of downstream event mean concentrations of magnesium under scenarios 1 (CarterLvl1), 2 (CarterLvl2), and 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

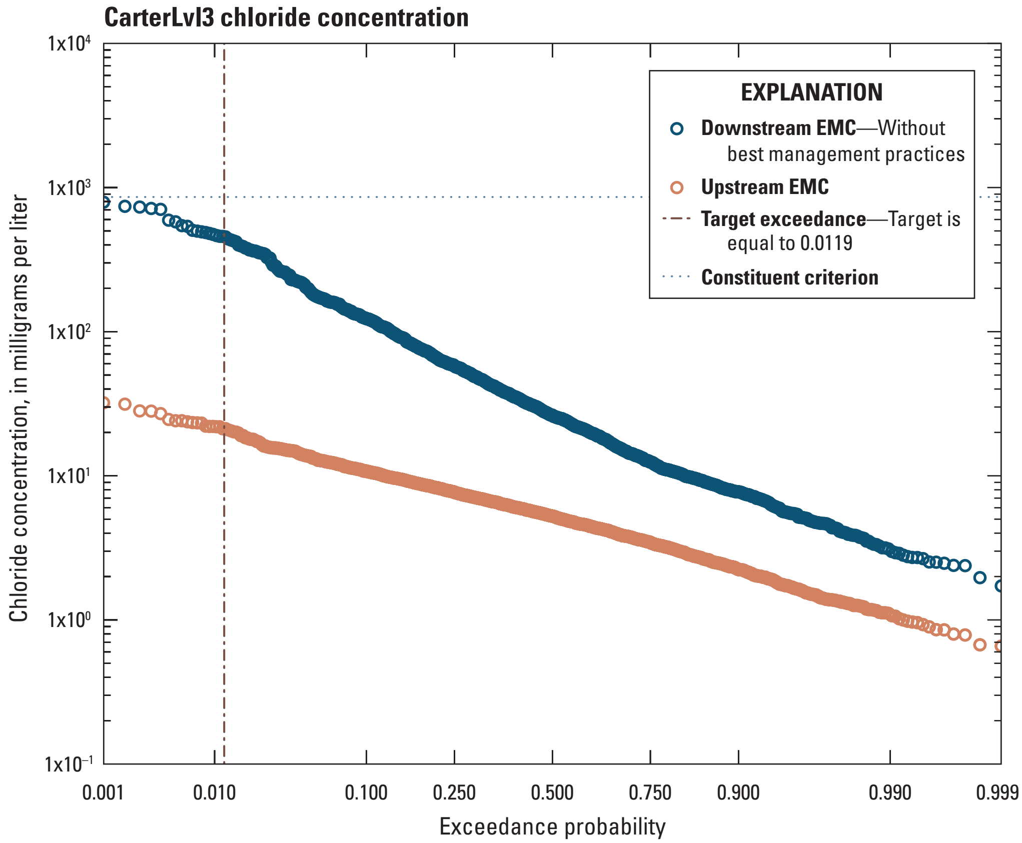


Figure 19. Exceedance probabilities of event mean concentrations of chloride upstream and downstream from the road crossing under scenario 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon. [EMC, event mean concentration.]

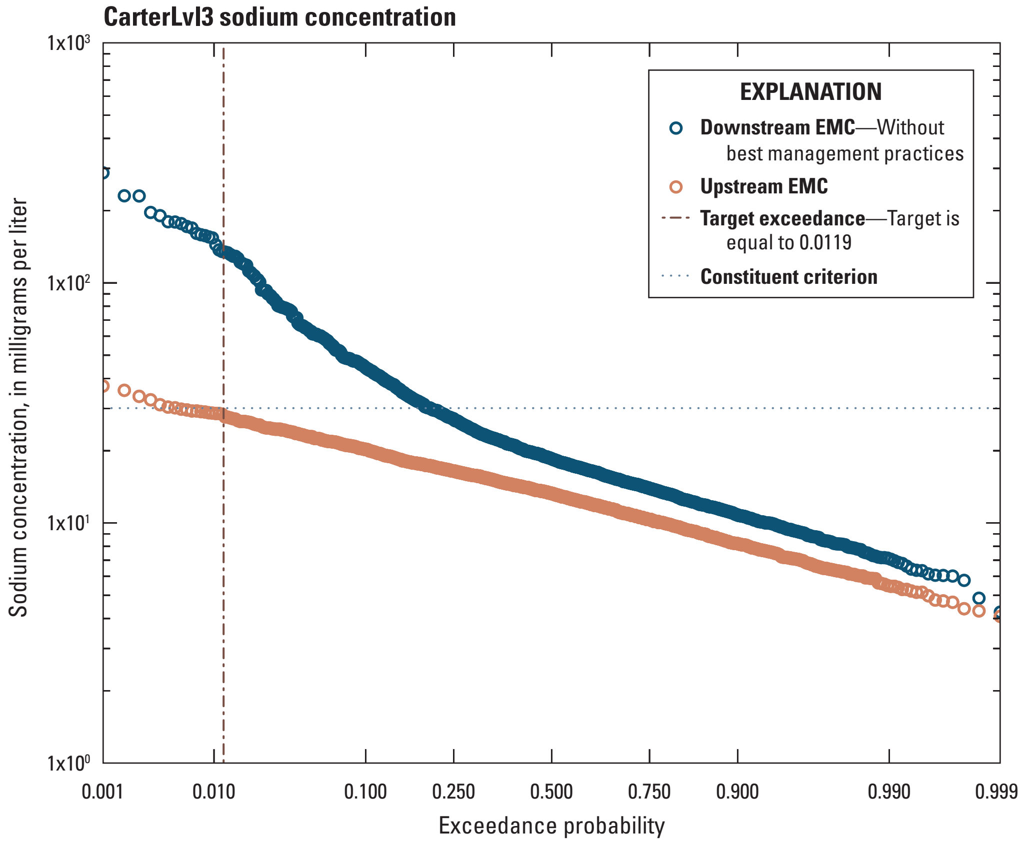


Figure 20. Exceedance probabilities of event mean concentrations of sodium upstream and downstream from the road crossing under scenario 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon. [EMC, event mean concentration.]

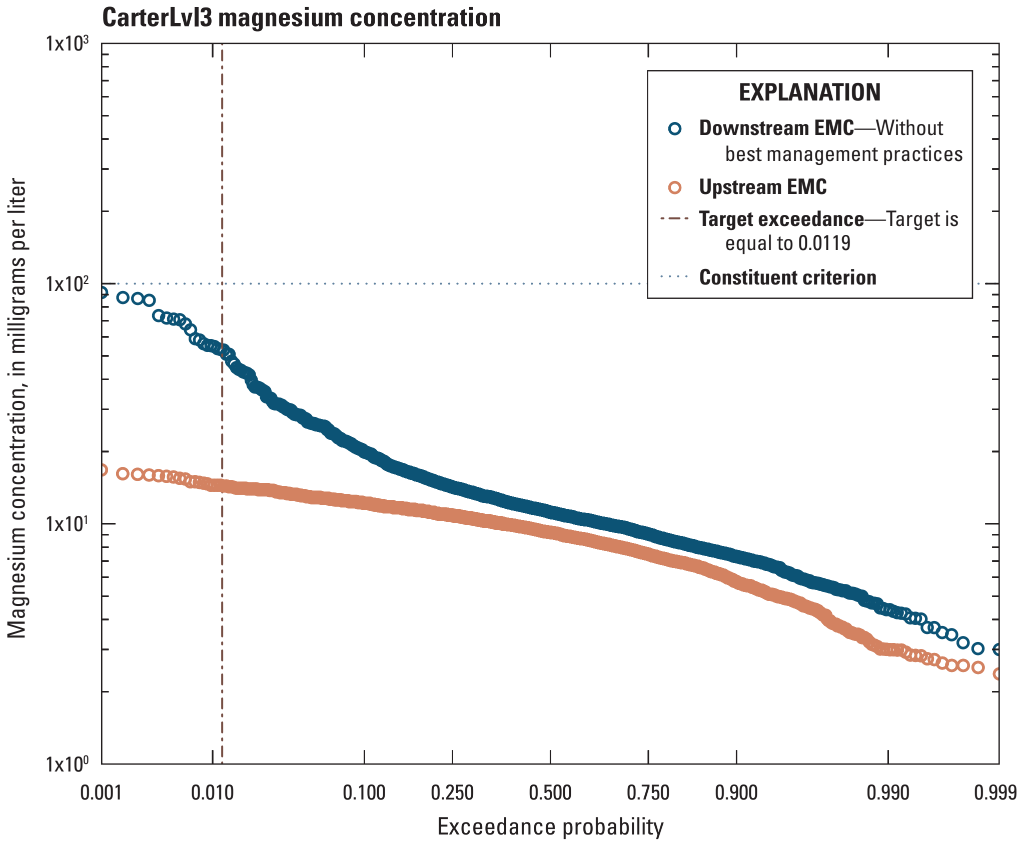


Figure 21. Exceedance probabilities of event mean concentrations of magnesium upstream and downstream from the road crossing under scenario 11 (CarterLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon. [EMC, event mean concentration.]

Sensitivity Analyses

SELDM scenarios 3–10 (table 3) were developed to evaluate the value of hydrologic and meteorological data collected for the level-3 analysis. These eight simulations were based on a level-2 analysis, but with input changed to reflect the presence or absence of specific hydrologic or meteorological data. For example, scenario 4 (CarterLvl2Pcp1) represents absence of regional or local precipitation data. Other input parameters not related to precipitation were based on the level-2 analysis data (CarterLvl2), but precipitation inputs were calculated from ecoregion data (default precipitation data in SELDM), which would reflect a level-1 analysis. Conversely, scenario 5 (CarterLvl2Pcp3) was identical to scenarios 2 and 4, with the exception of using local precipitation data instead of regional or ecoregion precipitation data. The purpose of scenario 5 was to evaluate the value of acquiring local precipitation data.

For all sensitivity analyses, most of the analysis was focused on chloride, not on magnesium or sodium. Results for magnesium and sodium typically were similar to those for chloride. Sensitivity analyses of magnesium or sodium are presented only when they deviate substantially from chloride results.

Precipitation Sensitivity Analysis

SELDM scenarios 4 and 5 (designated “CarterLvl2Pcp1” and “CarterLvl2Pcp3,” respectively) were developed to evaluate model sensitivity to exclusion of regional precipitation data or inclusion of local precipitation data. SELDM precipitation inputs are directly related to the quantities of stormflow and highway runoff generated. The mean volume of precipitation in a storm event derived using the regional precipitation data from Risley and Granato (2014) (0.59 inches, scenario 2) is about 70 percent of the same statistic derived using the rain zone (0.84 inches, scenario 4; table 7). There is a similar difference based on the mean volume derived from local precipitation data collected for a level-3 analysis (0.62 inches, table 7), indicating that the mean precipitation volume for the watershed may be similar to regional estimates. These variations are large but not surprising because the study area is in a mountainous part of Oregon where precipitation is highly variable from place to place depending on the aspect and elevation of the drainage basin (Daly and others, 1994). Differences in precipitation estimates may not be as pronounced in areas with less variability in aspect and elevation. Consequently, the mean volume of event streamflow flowing into the intersection of Carter Creek Branch 1 and I–5 differs among the three scenarios (fig. 22), with CarterLvl2Pcp1 (level-1 [rain zone] analysis of precipitation) estimating the largest median upstream flow and CarterLvl2 (level-2 [regional] analysis of precipitation) the smallest. Exceedance probabilities of highway runoff for the three scenarios followed the same pattern. The largest median highway runoff (not shown) was observed in CarterLvl2Pcp1, and the smallest in CarterLvl2.

The upstream, highway-runoff, and downstream flow EMCs of chloride were similar (fig. 23). The median EMCs of highway runoff for scenarios CarterLvl2Pcp1 (national precipitation data), CarterLvl2, and CarterLvl2Pcp3 (local precipitation data) were 67.3, 54.3, and 76.2 mg/L, respectively. The mean highway-runoff EMCs had similar levels of variability between scenarios, but at values about an order of magnitude higher than median highway-runoff EMCs because of the large value of skewness in the EMC population. The chloride highway-runoff input statistics were identical for all three scenarios, so the variability in EMCs resulted from the varying number of storms per year, the mean volume of precipitation per storm, and differences in random seed numbers in the Monte Carlo simulations of the SELDM model.

Despite the differences in highway-runoff EMCs of chloride, the downstream exceedance levels were similar, with the risk of exceeding the 860 mg/L water-quality CMC for chloride ranging between about 1.0 and 1.3 percent (fig. 24). Because these differences are within the range of water-quality variation expected if all events during the 39- year simulation period had been measured (Harmel and others, 2006), the results for this geographic area suggest that the absence of local precipitation data and the absence of a regional precipitation analysis would not result in large differences in rates or exceedance of the chloride criterion used for this study. However, because the exceedance rates of all three scenarios are close to the target exceedance probability of 1.19 percent, use of only the rain zone precipitation data (CarterLvl2Pcp1 scenario) would result in the conclusion that EMC targets are not being met (EMC values exceed the 860 mg/L CMC), whereas the use of the regional or local precipitation data would show that the rate of chloride exceedances (1.0 and 1.1 percent, respectively) meet the target exceedance probability.

Annual concurrent runoff loads of chloride simulated downstream from the road crossing were more variable between scenarios than were EMCs (fig. 25). Median annual concurrent runoff loads of chloride were highest using local precipitation data (CarterLvl3: 9,100 pounds) and lowest using regional precipitation data (CarterLvl2: 5,100 pounds). The higher median values from using local precipitation data in CarterLvl3 resulted in part from the dataset's containing the most storms per year. These results show that, assuming the derived precipitation estimates using local data are accurate, SELDM estimates simulated using regional precipitation data at this location would result in substantially underestimated values of annual concurrent runoff loading of chloride. Similarly, annual concurrent runoff loads simulated using rain zone data would also underestimate annual concurrent runoff loading of chloride relative to CarterLvl3, but not to the same extent as the use of regional data.

The source of these differences can be seen in table 7. Assuming the precipitation statistic estimates from local data are accurate, the rain zone data include too few events per year (35 compared to 50 events), but this negative bias (relative to CarterLvl3) is somewhat offset by overestimating the mean storm-event volume (0.84 compared to 0.62 inches). The offsetting biases result in a similar total precipitation volume from events (29.4 compared to 31.1 inches). Conversely, the regional data have a similar mean annual event volume but have a similar low bias in the number of events per year. This combination of statistics results in a total annual storm- event volume that is also biased low (21.1 inches, table 7).

Streamflow Sensitivity Analysis

SELDM scenarios 6 and 7 (designated "CarterLvl2Q1" and "CarterLvl2Q3," respectively) were designed to analyze the utility of streamflow data collected for this study. CarterLvl2Q1 and CarterLvl2Q3 were identical to scenario 2 (CarterLvl2) with the exception of the inputs for the streamflow statistics. For CarterLvl2Q1, streamflow statistical inputs from the default SELDM ecoregions were used, as would be used in a level-1 analysis. For CarterLvl2Q3, local data were used in a manner similar to a level-3 analysis.

CarterLvl2Q3 (using local streamflow data) estimated a smaller median streamflow volume than scenarios CarterLvl2 and CarterLvl2Q1 (default ecoregion streamflow data) (fig. 26). The flow-volume pattern (shape of the graph) differed between the three scenarios. At low exceedance probabilities (high flows), CarterLvl2Q3 estimated much less streamflow than CarterLvl2Q1, but a similar amount to CarterLvl2. Conversely, at low streamflows more representative of summer conditions, CarterLvl2Q3 estimated much less streamflow than scenario CarterLvl2, but a similar amount to CarterLvl2Q1. These results suggest that relative to CarterLvl2Q3, use of the regional streamflow data taken from the Bear Creek watershed would result in a high bias of low flows, whereas the use of ecoregion data would result in a high bias of high flows. Both regional and ecoregion data resulted in more streamflow variability than streamflow volumes estimated using local data, although some or all of this difference in variability could be partly owing to the methods used for extension of the streamflow time series.

Highway-runoff and upstream EMCs of chloride were identical for all three scenarios (fig. 27). This was because the precipitation inputs were identical, and each scenario had the same number of events. Combined with the identical seed number for stochastic number generation and identical water-quality constituent inputs, there was no possibility of differences through random number generation, similar to the sensitivity analysis for precipitation.

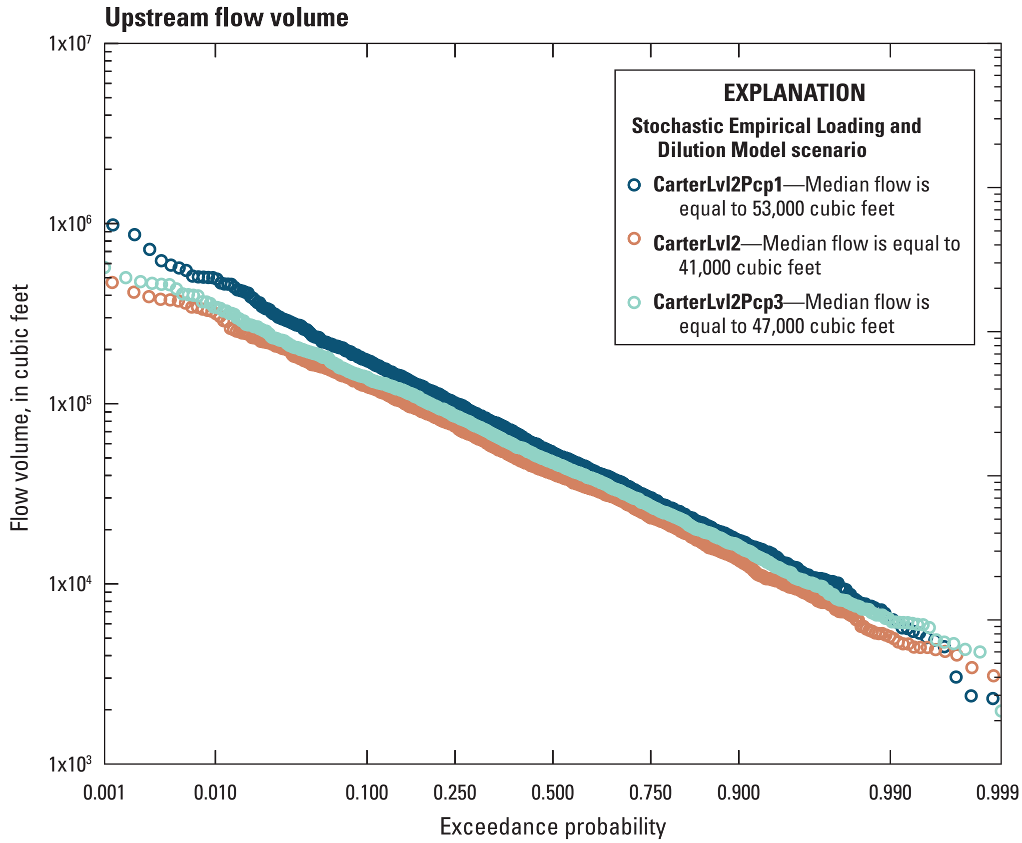


Figure 22. Exceedance probabilities of stormflow volumes under scenarios 4 (CarterLvl2Pcp1), 2 (CarterLvl2), and 5 (CarterLvl2Pcp3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

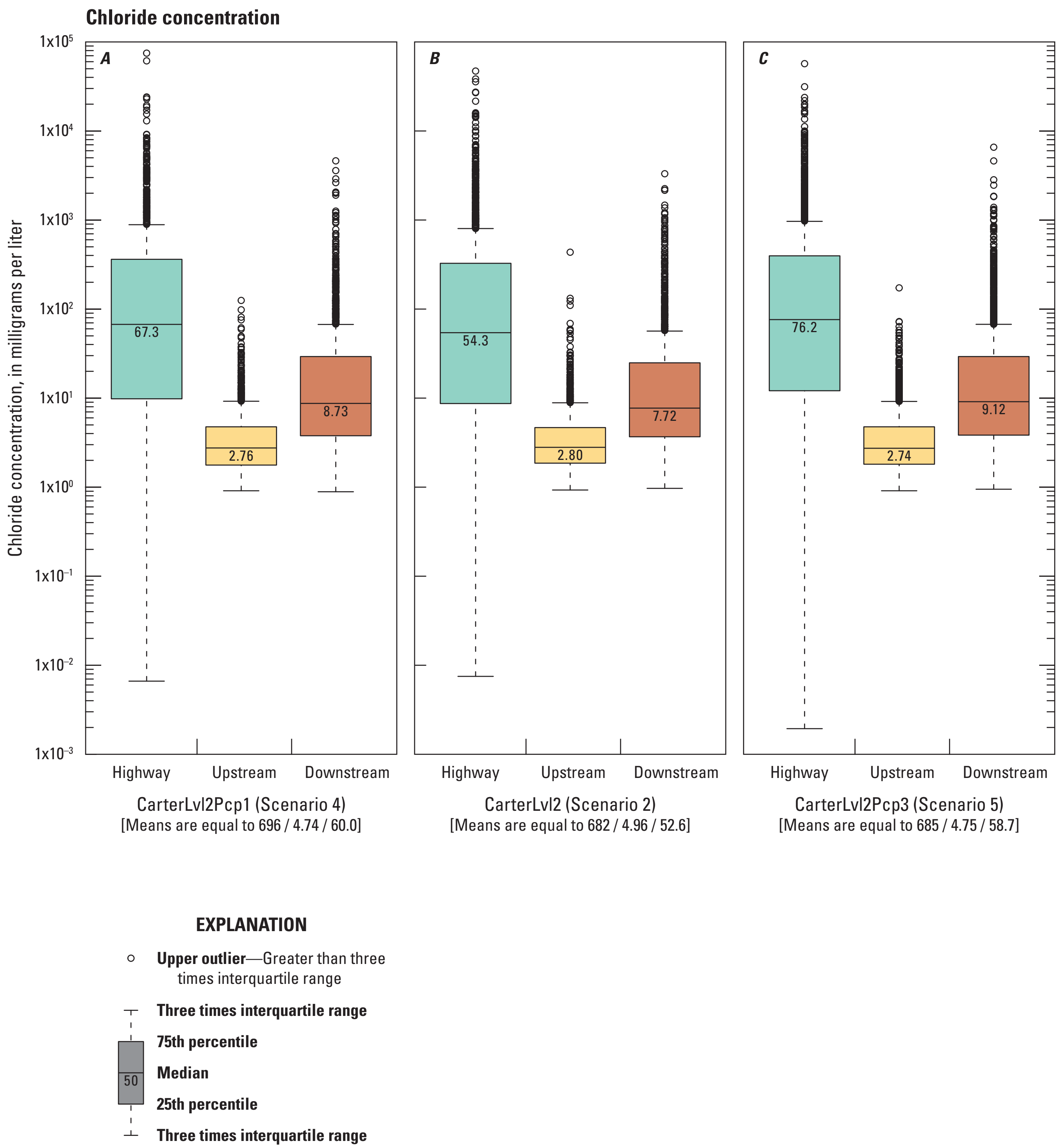


Figure 23. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 4 (CarterLvl2Pcp1), (*B*) 2 (CarterLvl2), and (*C*) 5 (CarterLvl2Pcp3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

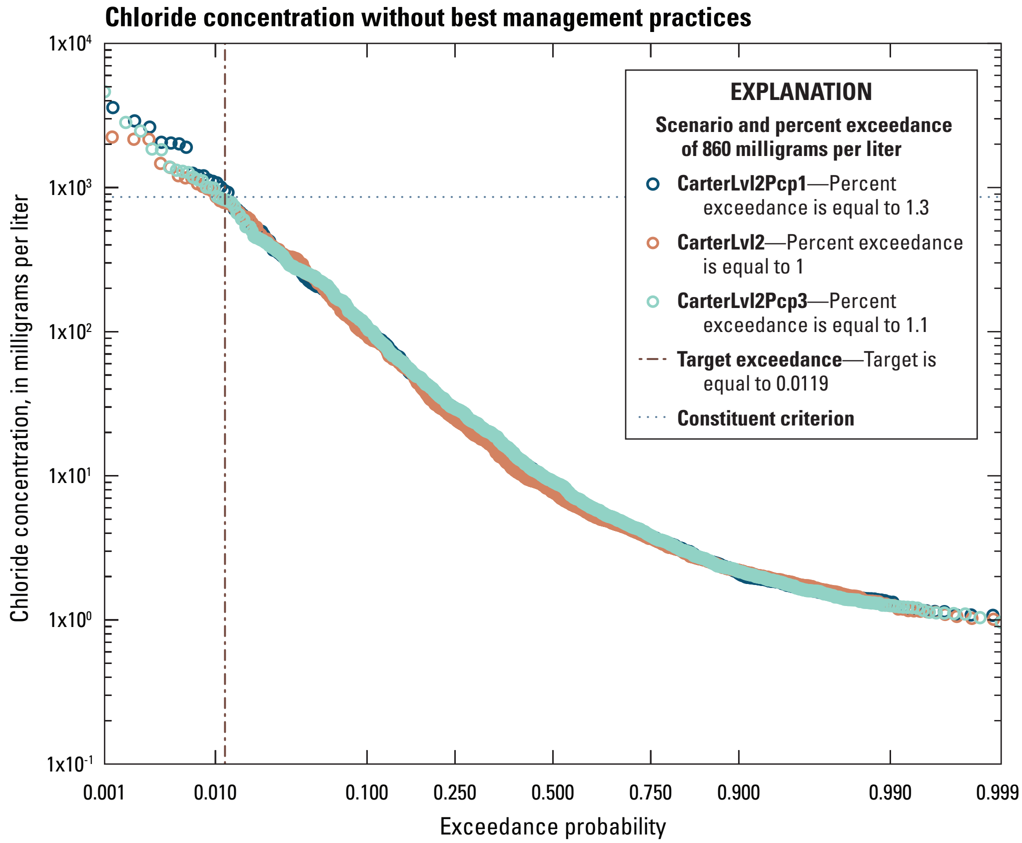


Figure 24. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 4 (CarterLvl2Pcp1), 2 (CarterLvl2), and 5 (CarterLvl2Pcp3) implemented at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

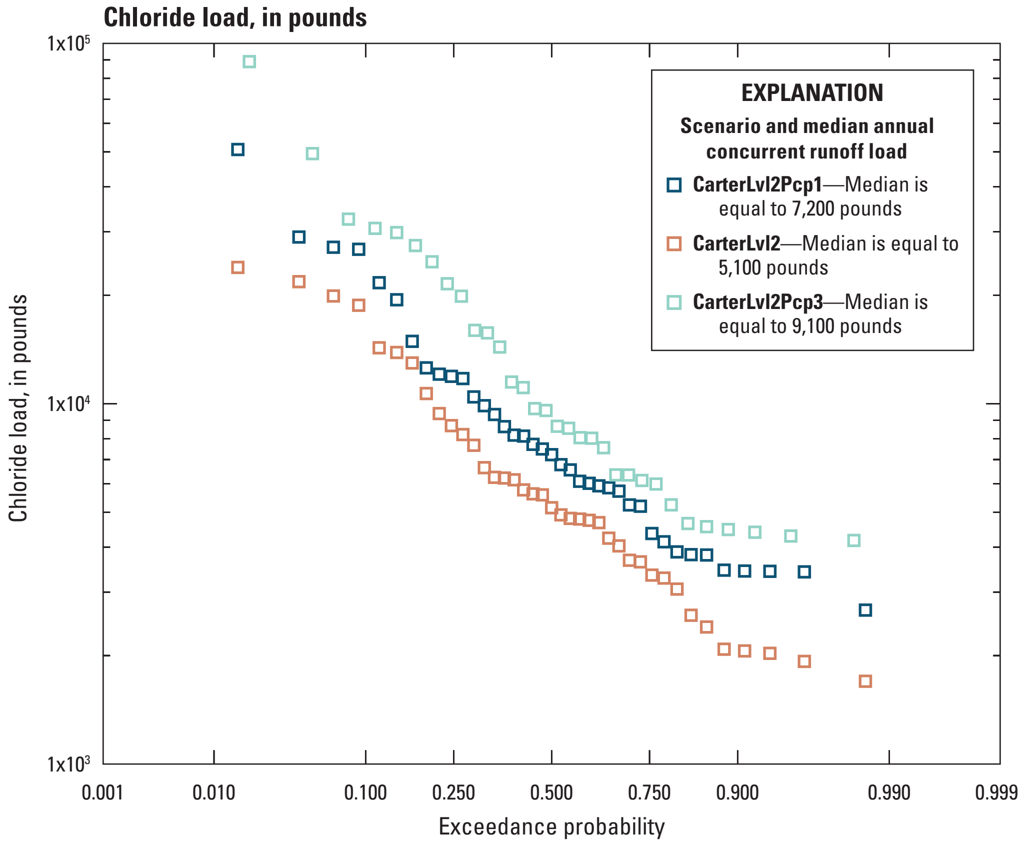


Figure 25. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 4 (CarterLvl2Pcp1), 2 (CarterLvl2), and 5 (CarterLvl2Pcp3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

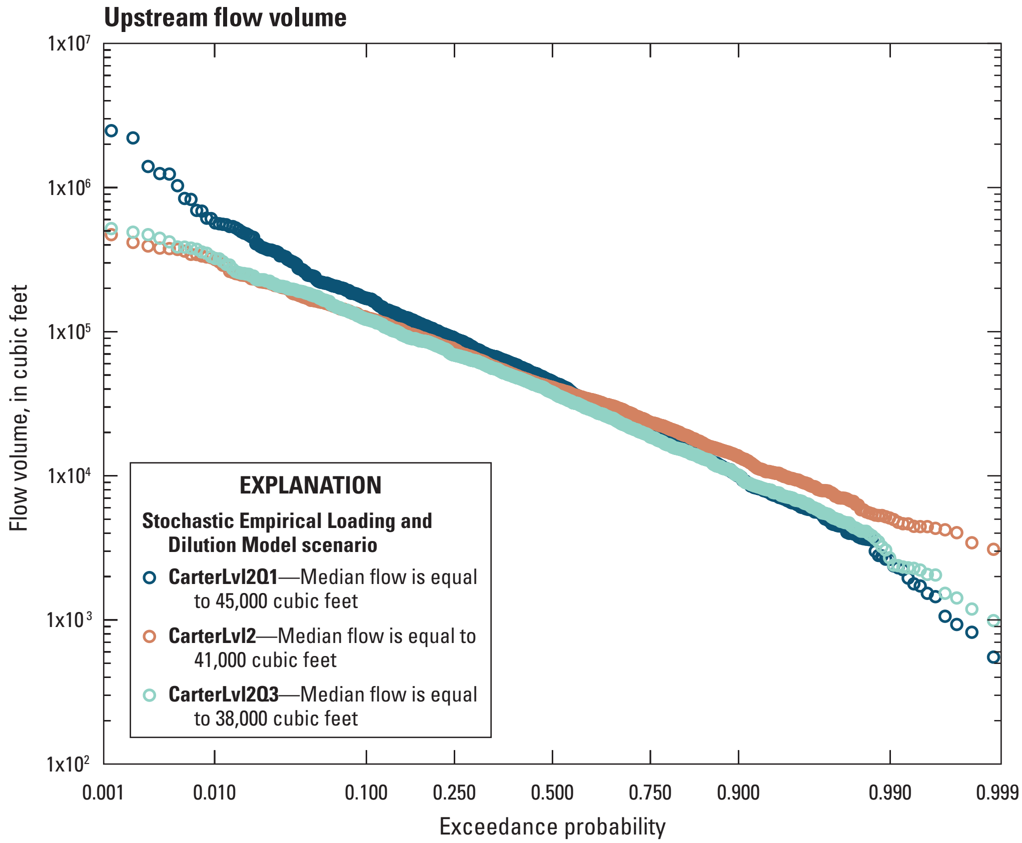


Figure 26. Exceedance probabilities of stormflow volumes under scenarios 6 (CarterLvl2Q1), 2 (CarterLvl2), and 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

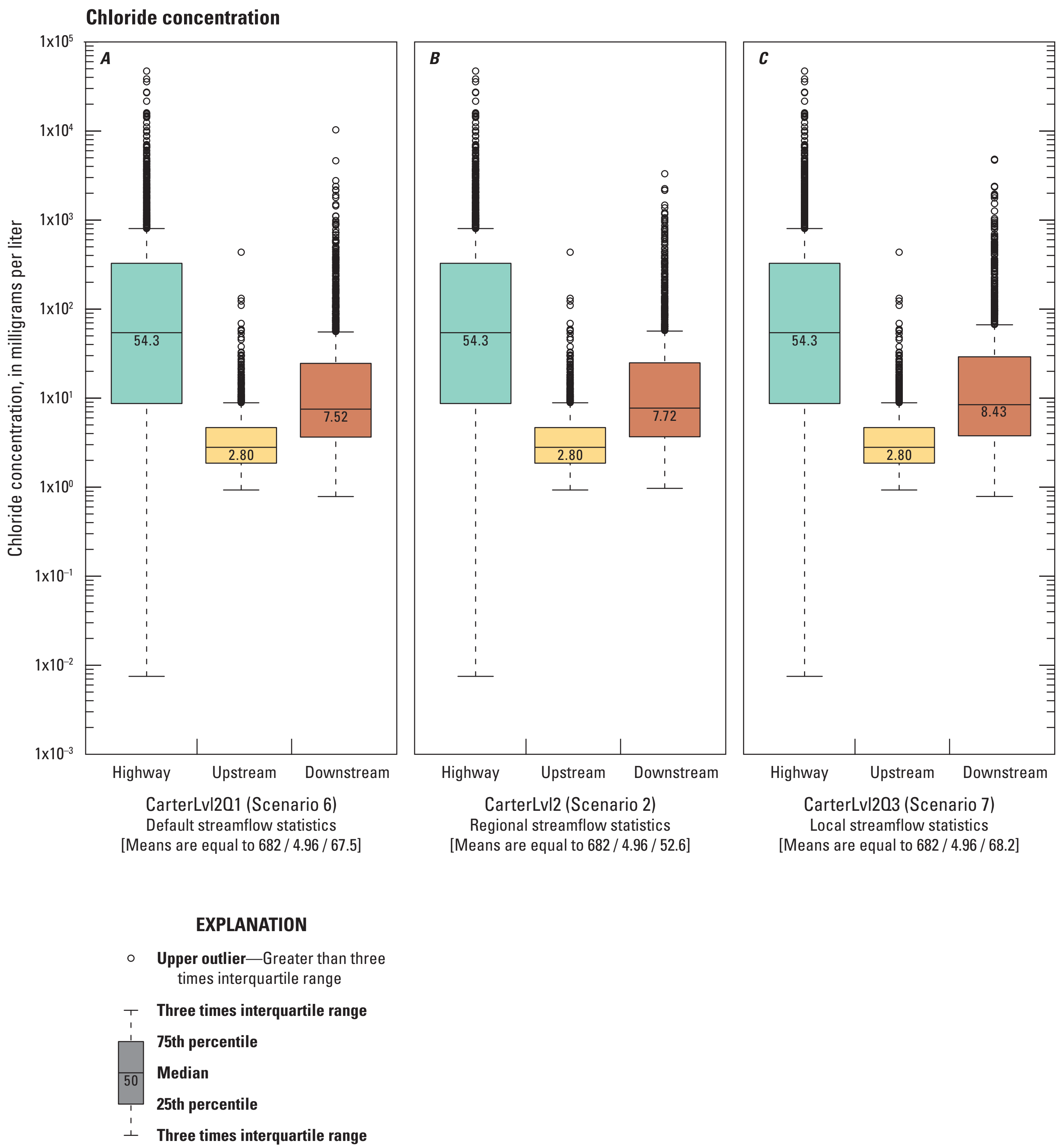


Figure 27. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 6 (CarterLvl2Q1), (*B*) 2 (CarterLvl2), and (*C*) 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Downstream EMCs of chloride, however, varied slightly between scenarios. More upstream streamflow results in a greater dilution of highway runoff, which has higher concentrations of chloride than streamflow. Consequently, the scenario with the least streamflow (CarterLvl2Q3) resulted in the highest downstream EMCs of chloride.

Because upstream, highway-runoff, and downstream EMCs of chloride were similar for all three scenarios, exceedance probabilities are also similar (fig. 28). The range of chances of exceeding the study chloride CMC for all three scenarios is within 0.4 percent (ranging from 1 to 1.4 percent), which is well within the uncertainty of water-quality measurements. All three scenarios resulted in exceedance rates near the target exceedance probability of 1.19 percent. At higher exceedance probabilities, the three scenarios estimated nearly identical EMCs.

The median annual concurrent runoff loads of chloride were similar for all three scenarios (fig. 29), with CarterLvl2Q3 estimating the largest median annual load. Annual chloride concurrent runoff loads for all three scenarios were also similar at both high and low exceedance probabilities. However, annual concurrent runoff loads varied differently for sodium (fig. 30) and magnesium (fig. 31) scenarios. For those two constituents, CarterLvl2Q1 estimated the largest mean annual concurrent runoff load. The difference is related to the percentage of the water-quality constituent annual concurrent runoff load that was derived from highway runoff compared to upstream. Because highway runoff and EMCs were held constant for all three scenarios, all disparities were derived from the different volumes of streamflow above the road crossing. For chloride, highway runoff represents about 90–94 percent of annual concurrent runoff loading (table 22). Consequently, small changes in upstream flow produce little change in downstream loading. Conversely, highway runoff represents about 26 to 36 percent of downstream annual concurrent runoff loading of magnesium from storm events. Consequently, changes in streamflow result in much larger differences in annual concurrent runoff load of magnesium relative to chloride.

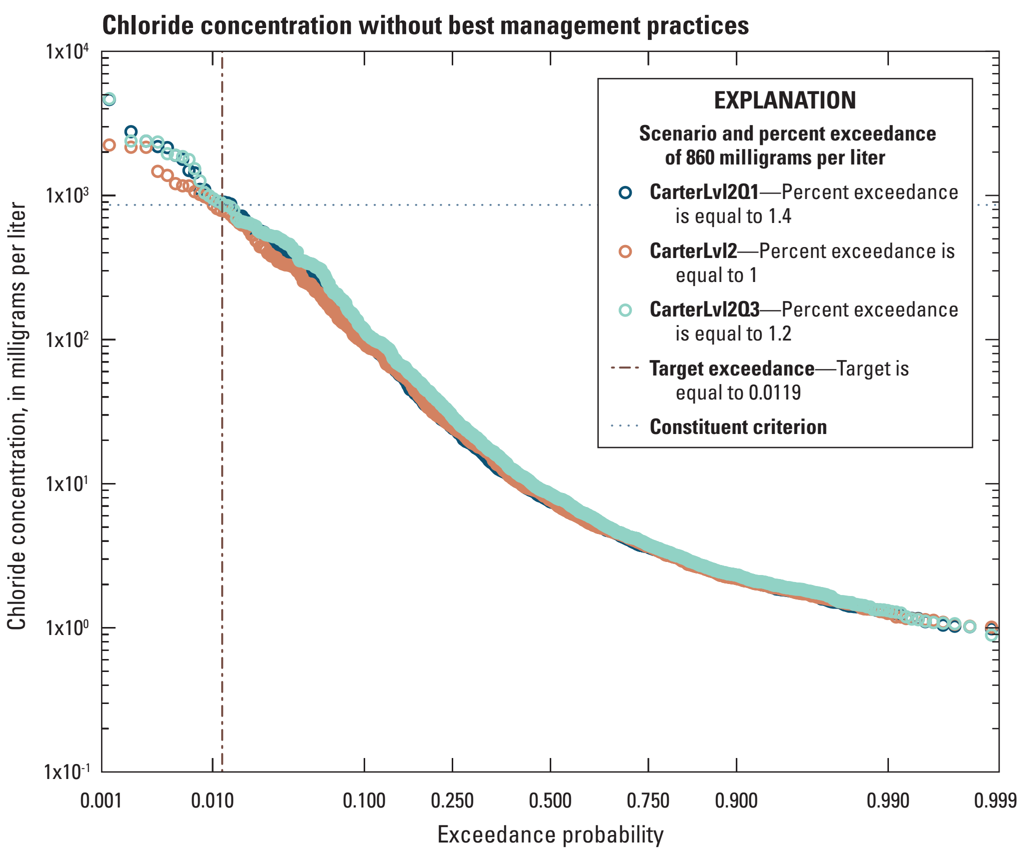


Figure 28. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 6 (CarterLvl2Q1), 2 (CarterLvl2), and 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

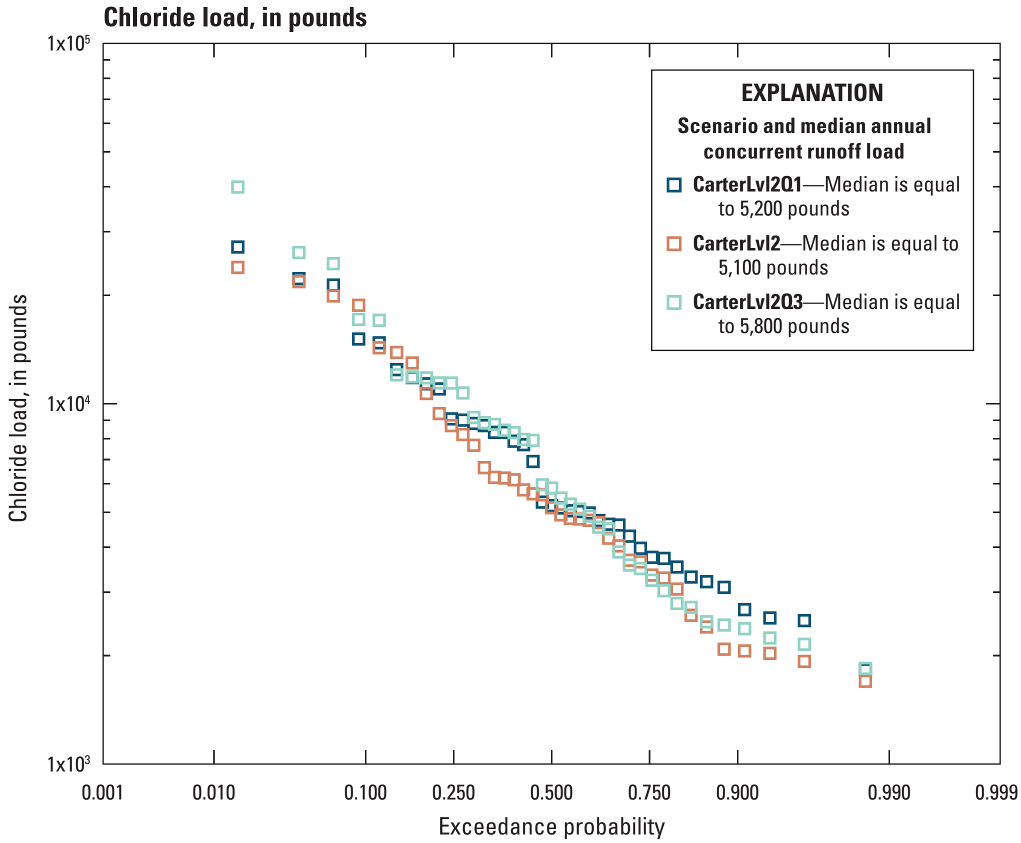


Figure 29. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 6 (CarterLvl2Q1), 2 (CarterLvl2), and 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

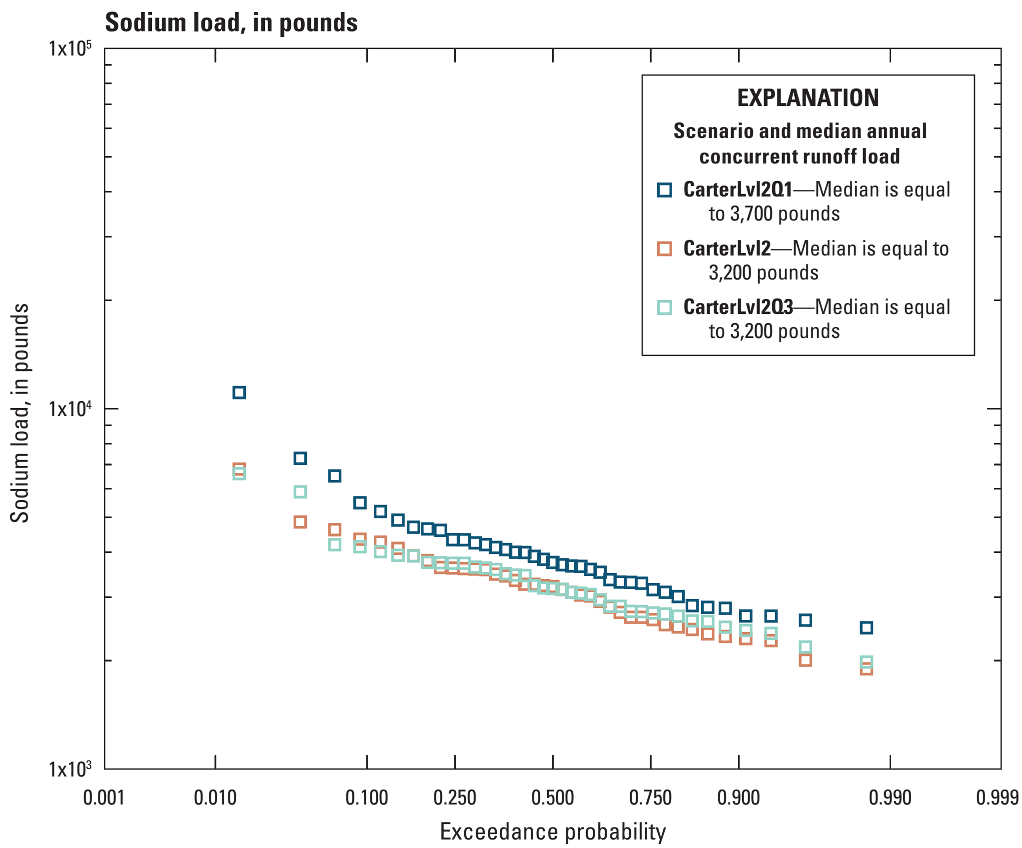


Figure 30. Exceedance probabilities of annual concurrent runoff loads of sodium under scenarios 6 (CarterLvl2Q1), 2 (CarterLvl2), and 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

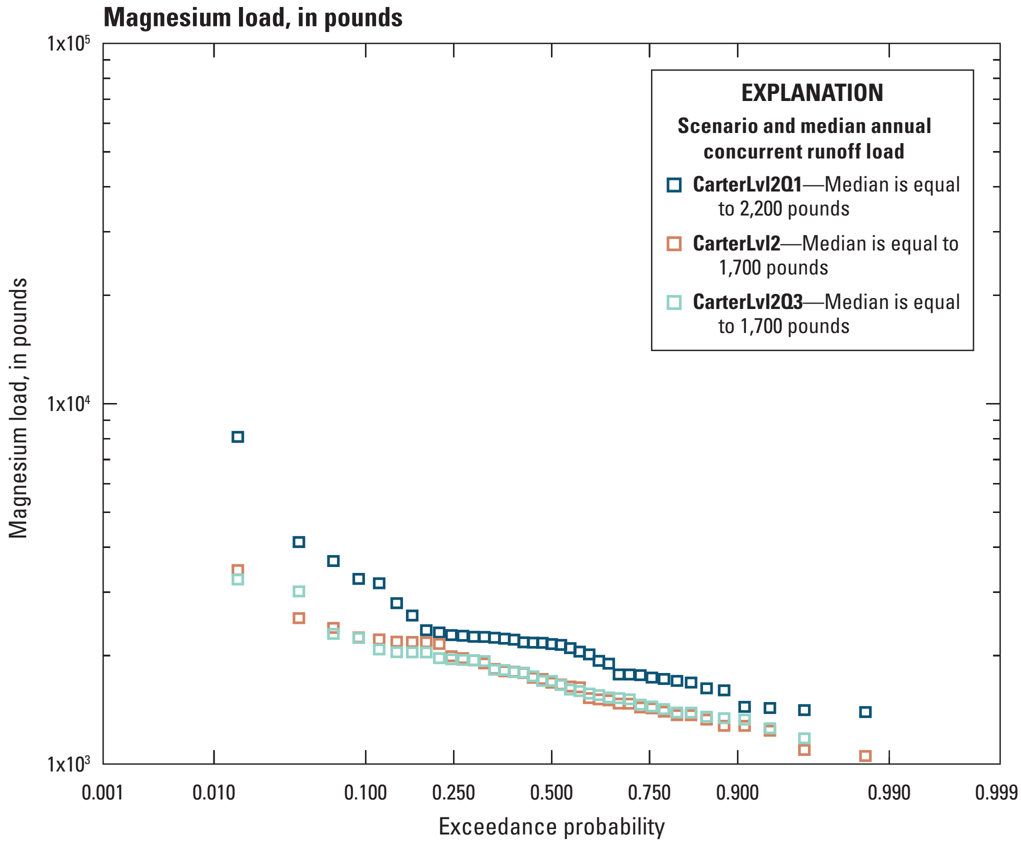


Figure 31. Exceedance probabilities of annual concurrent runoff loads of magnesium under scenarios 6 (CarterLvl2Q1), 2 (CarterLvl2), and 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Table 22. Percentage of annual concurrent runoff load of chloride, magnesium, and sodium from storm events represented by highway runoff for Stochastic Empirical Loading and Dilution Model scenarios 6 (CarterLvl2Q1), 2 (CarterLvl2), and 7 (CarterLvl2Q3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Scenario number	Scenario name	Scenario description	Chloride (percent)	Magnesium (percent)	Sodium (percent)
6	CarterLvl2Q1	Ecoregion flow	90.1	26.5	38.5
2	CarterLvl2	Regional flow	91.9	34.1	46.5
7	CarterLvl2Q3	Local flow	93.7	36.5	49.4

Upstream Chloride Concentration Sensitivity Analysis

SELDM scenarios 8 and 9 (designated “CarterLvl2UpstrConcLoc” and “CarterLvl2UpstrConcLoc3,” respectively) were designed to analyze the value of local and regional data acquisition of upstream concentrations of chloride. CarterLvl2UpstrConcLoc2 and CarterLvl2UpstrConcLoc3 are identical to CarterLvl2 with the exception of upstream chloride concentrations. For CarterLvl2UpstrConcLoc2, the statistics used to derive the population of random upstream chloride concentrations were calculated from the regional data collected in the greater Bear Creek watershed as part of this study. This is considered a more realistic estimate of background chloride concentrations compared to the regional data used in CarterLvl2 in which chloride concentrations were taken from a larger geographic area (the Pacific Northwest). CarterLvl2UpstrConcLoc3 uses local data and is based on specific conductance data collected just upstream from the highway-creek intersection and the specific conductance-chloride relation derived from regional data to estimate upstream chloride concentration population parameters. The use of local data in CarterLvl2UpstrConcLoc3 probably results in a more representative estimate of upstream concentrations of chloride.

Highway-runoff EMCs of chloride were identical for all three scenarios (fig. 32) because the highway-runoff and precipitation parameters were consistent between the scenarios. Mean and median upstream EMCs of chloride were small and roughly consistent between all three scenarios, although EMCs for scenario CarterLvl2UpstrConcLoc2 (regional constituent-concentration data from Bear Creek watershed) were slightly higher than in the other two scenarios. The smallest upstream EMCs of chloride occurred with scenario CarterLvl2.

The downstream EMCs of chloride varied moderately between the three scenarios, with mean values ranging from about 53 to 73 mg/L and median values ranging from about 8 to 17 mg/L. The lowest mean values occurred in CarterLvl2, suggesting that reliance on only national data would result in an underestimation of downstream EMCs of chloride relative to CarterLvl2UpstrConcLoc3. Conversely, the highest downstream EMCs of chloride from CarterLvl2UpstrConcLoc2 suggest that a reliance on regional data from the Bear Creek watershed would result in a modest overestimation of downstream EMCs of chloride relative to CarterLvl2UpstrConcLoc3.

The downstream EMCs of chloride outliers in figure 32 are relatively consistent for the three scenarios, and, consequently, the EMCs for low exceedance probability events are consistent for all three scenarios (fig. 33). In all three scenarios the risk for chloride-CMC exceedances (860 mg/L) were between 1 and 1.2 percent, which are close to the one event in 3-year risk prescribed by the EPA. There were some larger divergences at higher exceedance probabilities, but, in general, all three simulations followed the same pattern. CarterLvl2UpstrConcLoc3 generally estimated the least variation in downstream EMCs across the full range of exceedance probabilities, with the exception of extreme exceedance probability values (above 0.99 and below 0.01).

Annual concurrent runoff loads of chloride from storm events were moderately variable between the three scenarios (fig. 34). Annual loads from CarterLvl2UpstrConcLoc2 were generally higher than loads from scenarios CarterLvl2 and CarterLvl2UpstrConcLoc3. With the exception of the very high and very low exceedance probabilities, EMCs tended to be consistent for all three scenarios. These results show that the acquisition of local upstream chloride and specific conductance data did not have a substantial effect on final concurrent runoff load results. Part of the reason for the lack of variability in load results is the relative consistency in upstream EMCs for all three scenarios. The other important factor is that a large percentage of the annual load downstream from the site was derived from highway runoff rather than streamflow upstream from the intersection. Highway runoff accounted for between 80 and 92 percent of the annual concurrent runoff load (table 23). As such, small to moderate differences in upstream concentrations had relatively little effect on annual concurrent storm loads.

Highway-Runoff Chloride Concentration Sensitivity Analysis

SELDM scenario 10 (designated “CarterLvl2HwyConcLvl3”) was designed to analyze the value of local-data acquisition of highway-runoff EMCs of chloride. CarterLvl2HwyConcLvl3 is identical to scenario 2 (CarterLvl2) with the exception of highway-runoff chloride EMCs. CarterLvl2HwyConcLvl3 uses specific conductance data collected from I–5 highway runoff (USGS station 420425122361700) and the specific conductance-chloride relation derived from the samples collected from the autosampler on site. The use of local data in CarterLvl2HwyConcLvl3 should result in a more representative estimate of highway-runoff EMCs of chloride than the calculations from CarterLvl2.

Upstream EMCs of chloride were identical for scenarios CarterLvl2 and CarterLvl2HwyConcLvl3 (fig. 35), because the upstream EMC and precipitation parameters were consistent between the two scenarios. The highway-runoff EMCs of chloride from CarterLvl2HwyConcLvl3 had substantially less variability and less skew than from CarterLvl2. This is evident in the ratio of mean to median values. Whereas the mean highway-runoff EMC of chloride is more than 1 order of magnitude greater than the median in CarterLvl2, the mean is less than twice the median in CarterLvl2HwyConcLvl3. The greater variability and skew in CarterLvl2 also resulted in a mean highway-runoff EMC of chloride that was greater than in CarterLvl2HwyConcLvl3, but a median value that was substantially less (about 54 and 297 mg/L, respectively).

The downstream EMCs of chloride in the two scenarios resemble the results for the highway-runoff EMCs, but to a lesser degree (fig. 35). The median value of EMCs increased from about 8 to 21 mg/L between CarterLvl2 and CarterLvl2HwyConcLvl3, and the mean decreased from about 53 to 41 mg/L. These results show that without the acquisition of local highway-runoff chloride data, SELDM estimates of downstream and especially highway-runoff EMCs would have greater variability than was observed.

The smaller variability in the downstream EMCs of chloride for CarterLvl2HwyConcLvl3 is evident in the chloride EMC exceedance probability plot (fig. 36), in which the points for CarterLvl2HwyConcLvl3 produce a much more gradual slope than the results from CarterLvl2. For CarterLvl2HwyConcLvl3, this results in an exceedance probability of the chloride CMC used for this study of less than one-tenth of 1 percent, which easily meets the target probability of 1.19 percent. These results show not only that the use of regional rather than local highway-runoff chloride data would result in a higher probability of exceeding the study chloride CMC but would also result in a bias of low chloride EMCs for mid- and high exceedance probabilities relative to CarterLvl2HwyConcLvl3.

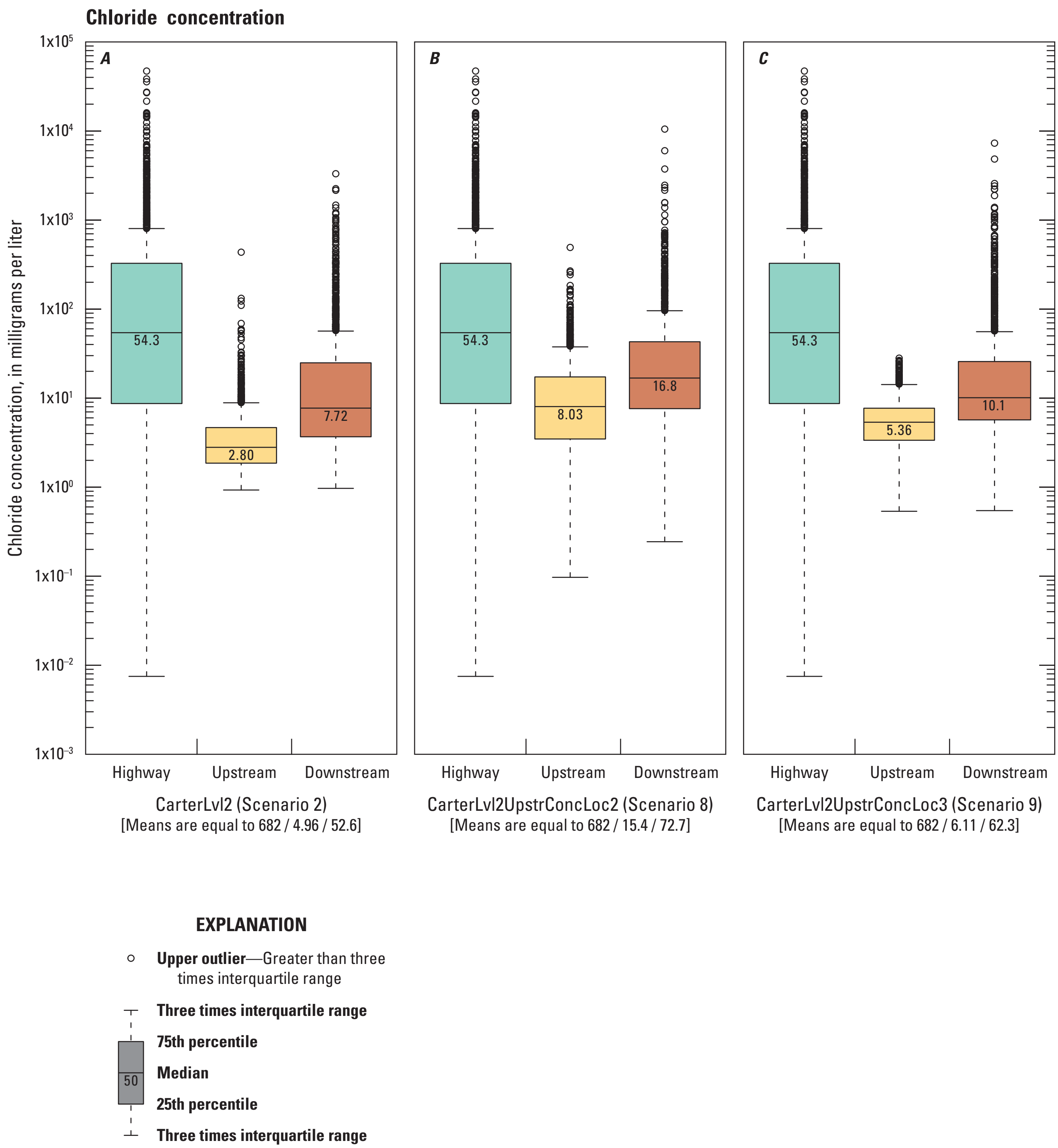


Figure 32. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 2 (CarterLvl2), (*B*) 8 (CarterLvl2UpstrConcLoc2), and (*C*) 9 (CarterLvl2UpstrConcLoc3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

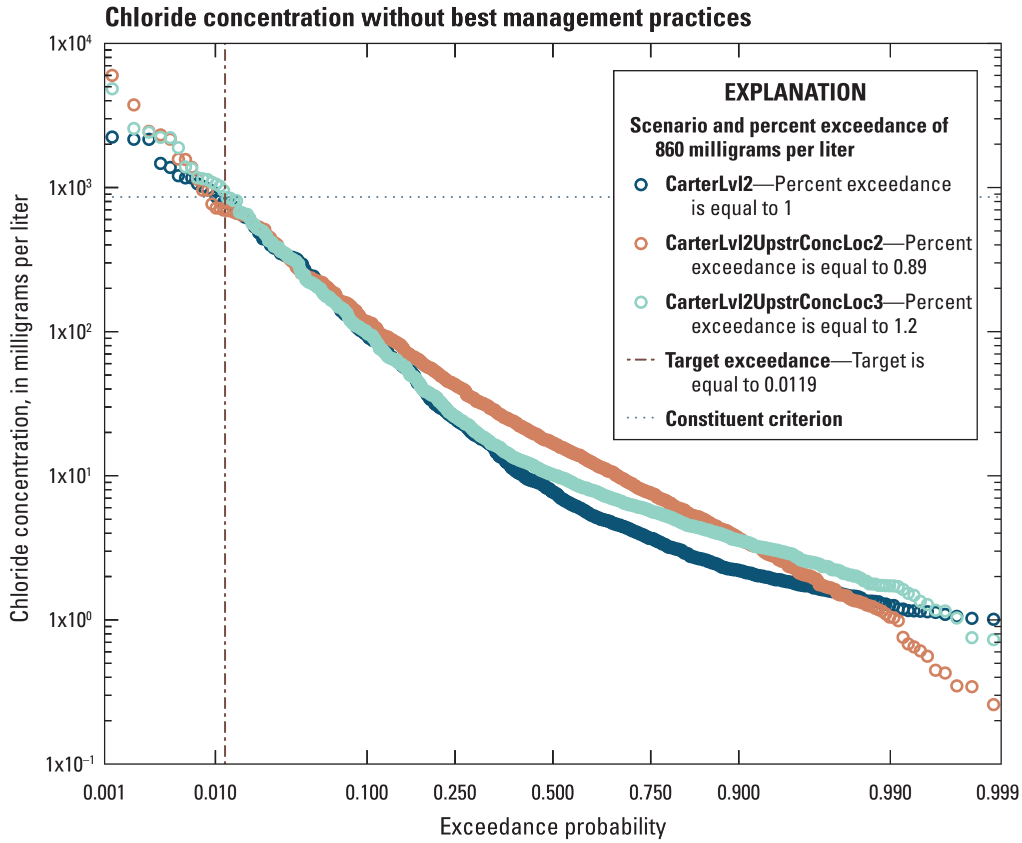


Figure 33. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios (*A*) 2 (CarterLvl2), (*B*) 8 (CarterLvl2UpstrConcLoc2), and (*C*) 9 (CarterLvl2UpstrConcLoc3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

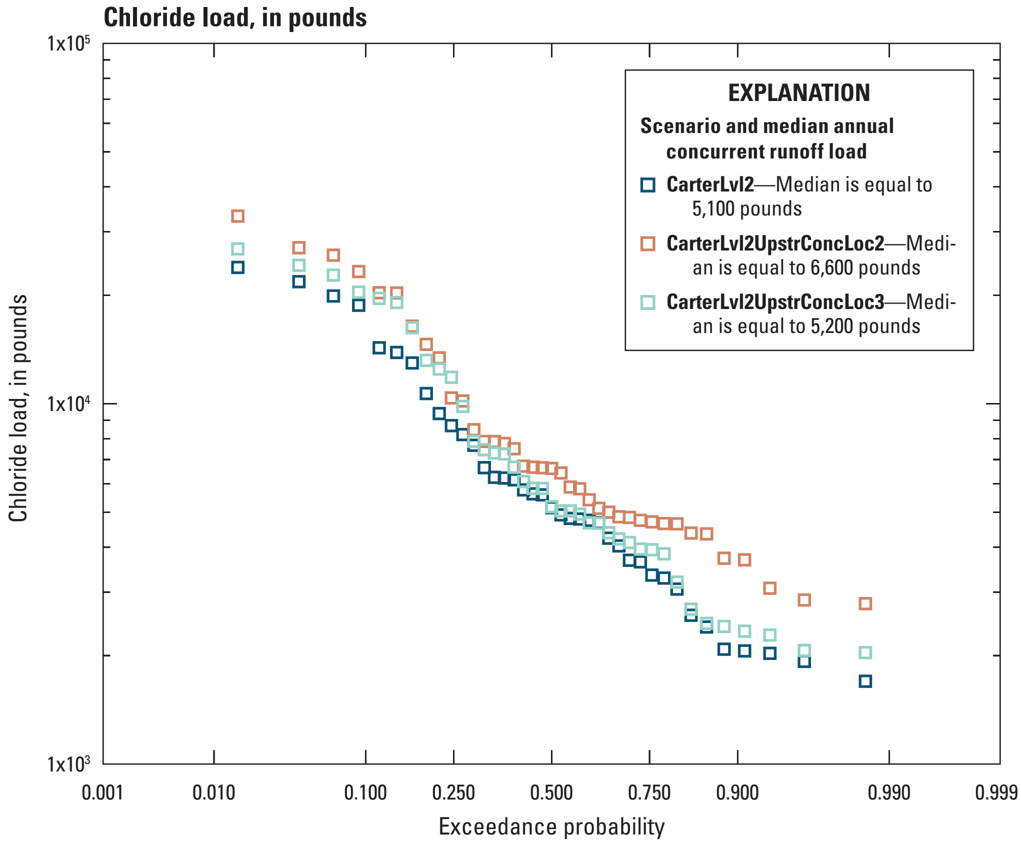


Figure 34. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 2 (CarterLvl2), 8 (CarterLvl2UpstrConcLoc2), and 9 (CarterLvl2UpstrConcLoc3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Table 23. Percentage of annual concurrent storm load of chloride represented by highway runoff for SELDM scenarios 2 (CarterLvl2), 8 (CarterLvl2UpstrConcLoc2), and 9 (CarterLvl2UpstrConcLoc3) in Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Scenario number	Scenario name	Input data source of upstream chloride concentrations	Chloride (percent)
2	CarterLvl2	Regional	91.9
8	CarterLvl2UpstrConcLoc2	Greater Bear Creek watershed	80.3
9	CarterLvl2UpstrConcLoc3	Carter Creek	90.9

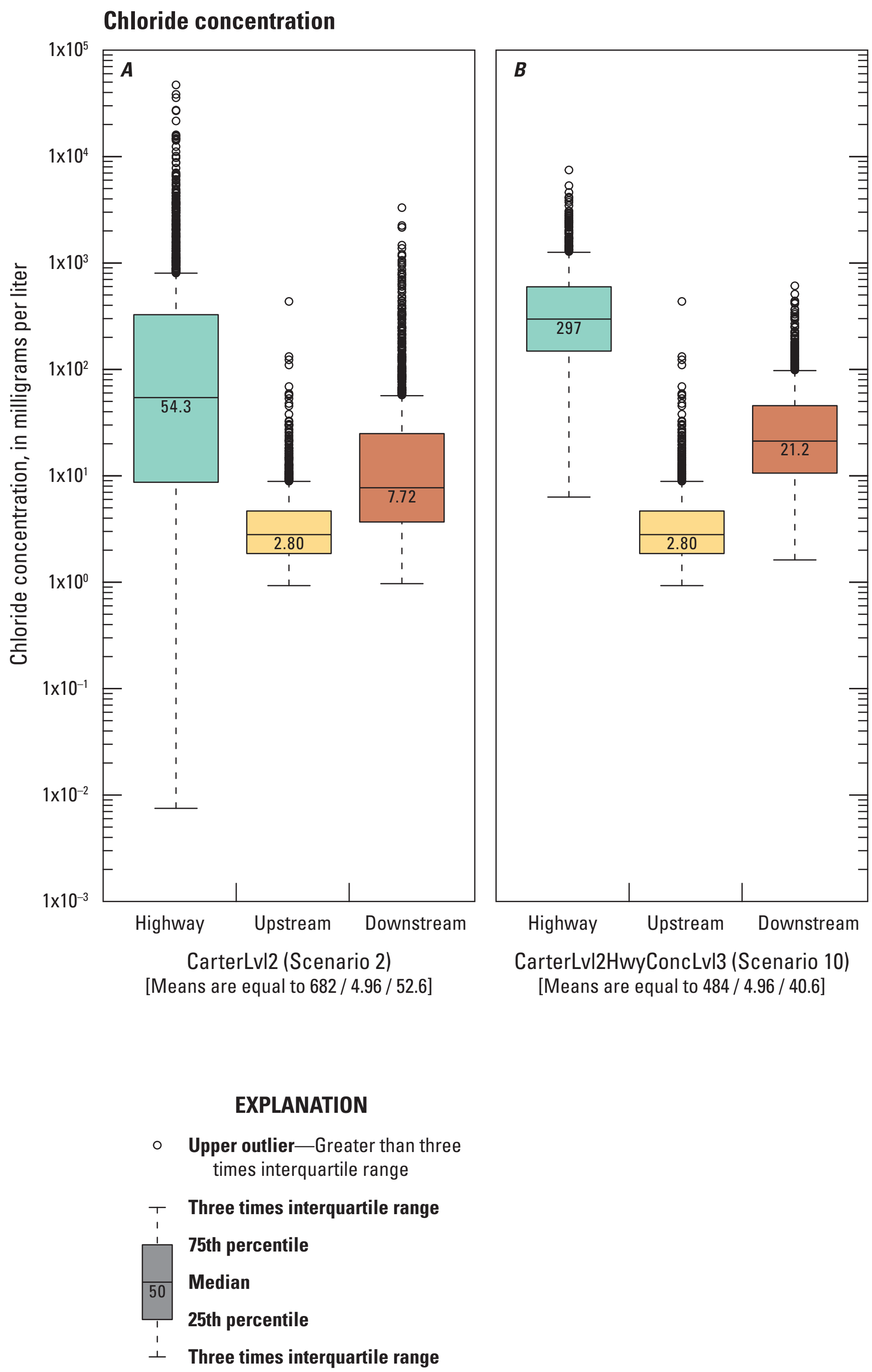


Figure 35. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 2 (CarterLvl2) and (*B*) 10 (CarterLvl2HwyConcLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

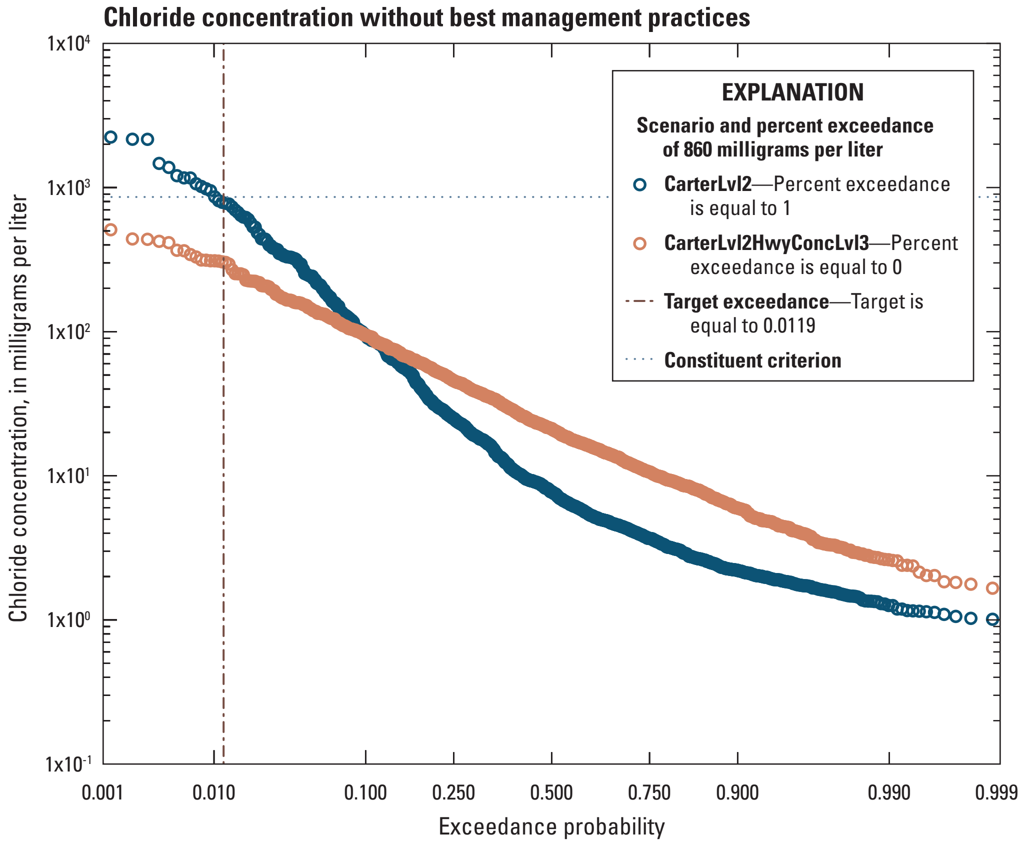


Figure 36. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 2 (CarterLvl2) and 10 (CarterLvl2HwyConcLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Annual concurrent runoff loads of chloride from storm-event probability plots for both scenarios have a similar pattern to those in the EMC probability plots (fig. 37). Annual concurrent runoff loads from CarterLvl2HwyConcLvl3 were lower than loads from CarterLvl2 at low exceedance probabilities, and higher than CarterLvl2 at high exceedance probabilities. The percentage of annual concurrent runoff chloride loading was lower for CarterLvl2HwyConcLvl3 (about 90 percent for CarterLvl2HwyConcLvl3 and 92 percent for CarterLvl2; table 24). For both scenarios, most of the annual concurrent runoff loading is derived from highway runoff.

Although local-concentration data provide the most representative estimates for the Carter Creek sites, data are not available for most highway sites across Oregon and, even if data are available at a particular site, these data may not characterize conditions that occur before a change in highway management is made. For example, if water-quality data were collected before the use of NaCl, then the relation of specific conductance to magnesium, chloride, and sodium would be different, and the range of specific conductance would be different. In any simulation, data from a short period must be used to simulate conditions that may occur over a long period of time. Total loads can vary substantially from year to year. For example, Granato (1996) found that deicing applications varied by a factor of 3.5 over a 4-year period, as did the number and severity of monitored events, and, therefore, the sample statistics are likely to vary substantially from year to year.

Volumetric Runoff Coefficient Sensitivity Analysis

SELDM scenario 3 (designated “CarterLvl2VR3”) was designed to analyze the value of calculating volumetric runoff coefficient statistics for highway and upstream runoff. CarterLvl2VR3 (values based on local volumetric runoff data) is identical to CarterLvl2 with the exception of the volumetric runoff coefficient statistics. In SELDM, the default statistical values for volumetric runoff coefficients are derived using relations between imperviousness and the volumetric runoff coefficient statistics. These relations were developed using national statistics (Granato, 2012). The use the national statistics assumes a similar set of relations at the site of study to average national conditions. For instances where the study site is fairly typical, such an assumption should produce acceptable volumetric runoff coefficient statistics and preclude the need to collect local data (highway runoff, upstream flow,

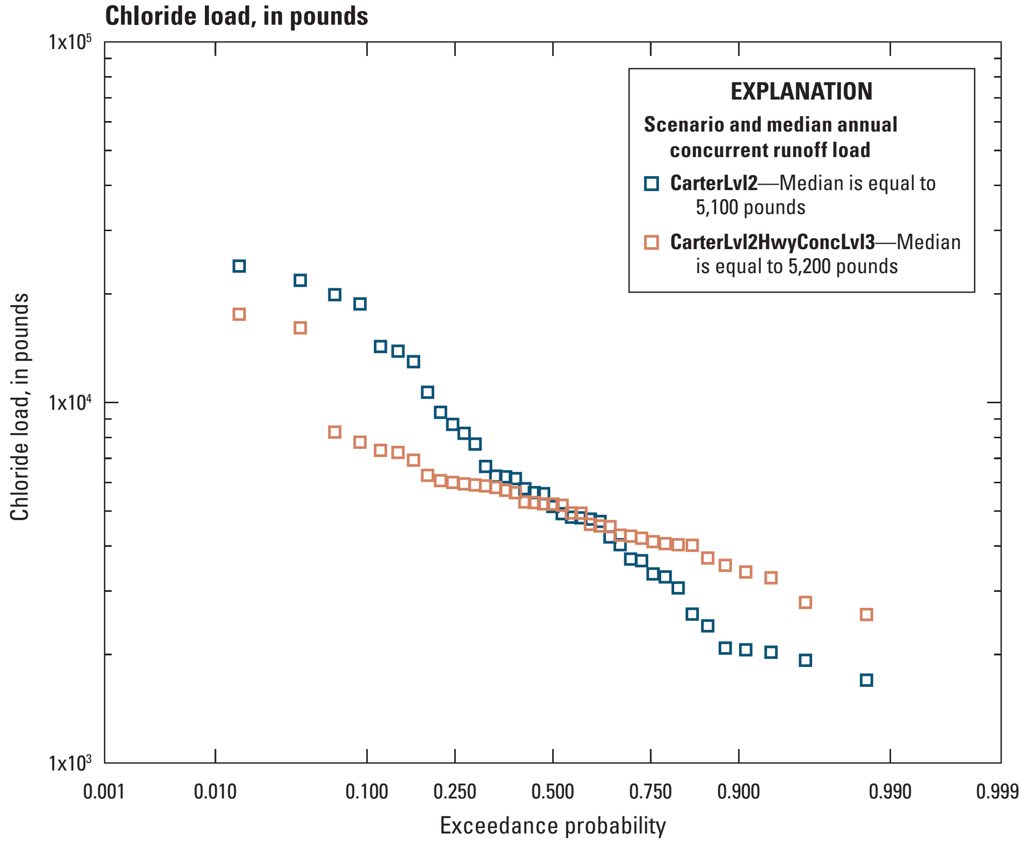


Figure 37. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 2 (CarterLvl2) and 10 (CarterLvl2HwyConcLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Table 24. Percentage of annual concurrent storm load of chloride represented by highway runoff for SELDM scenarios 2 (CarterLvl2) and 10 (CarterLvl2HwyConcLvl3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Scenario number	Scenario name	Input data source of highway runoff chloride concentrations	Chloride load (percent)
2	CarterLvl2	Regional	91.9
10	CarterLvl2Hwy-ConcLvl3	Local values	90.0

and precipitation) to calculate local statistics. For instances where the true volumetric runoff coefficient statistics are atypical (for example, if pervious pavement were used to create the roadway), the absence of such data may result in biased results.

Note that although this scenario evaluates only volumetric runoff coefficient values, in practice, the collection of the other, local data needed to calculate volumetric runoff coefficients would also produce local statistics for upstream flow, highway runoff, and precipitation. Note also that I–5 in the study area was surmised to be typical of interstate highway conditions and likely to produce volumetric runoff coefficients relatively in line with those derived from national data, with the minor exception of steeper-than-average slopes having the potential to result in increased volumetric runoff coefficients.

The volumetric runoff coefficient statistics varied little between scenarios CarterLvl2 and CarterLvl2VR3 (table 12). The highway-runoff coefficient statistics for CarterLvl2VR3 had a lower mean and greater standard deviation and skew compared to CarterLvl2. The relation between CarterLvl2 and CarterLvl2VR3 was similar for the upstream-runoff coefficient statistics in which CarterLvl2VR3 had the same mean and a greater standard deviation and skew compared to CarterLvl2. These statistics suggest that simulated runoff at both locations will average lower but contain more variability and more high outliers (because of greater values of skewness).

The volume of upstream-runoff events was similar at most exceedance probabilities for both scenarios (fig. 38). At higher exceedance probabilities (> 0.5), the volume of flow in CarterLvl2 was greater than for CarterLv12VR3. For all other exceedance probabilities, volumes were similar. These results suggest that the statistics used to define the population of upstream volumetric runoff coefficients were similar to the national distribution. Highway-runoff volumes had a similar pattern and were consistent between the two scenarios at lower exceedance probabilities (< about 0.25) but diverged at higher exceedance probabilities (fig. 39).

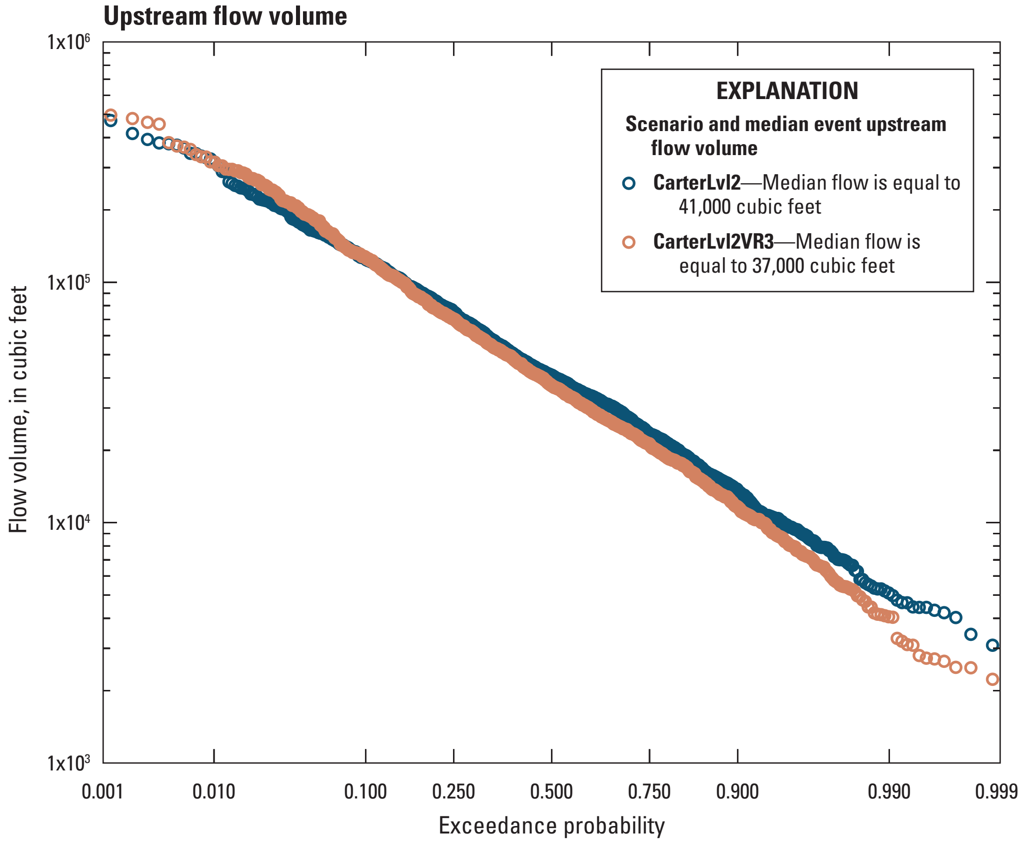


Figure 38. Exceedance probabilities of upstream stormflow volumes under scenarios 2 (CarterLvl2) and 3 (CarterLvl2VR3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

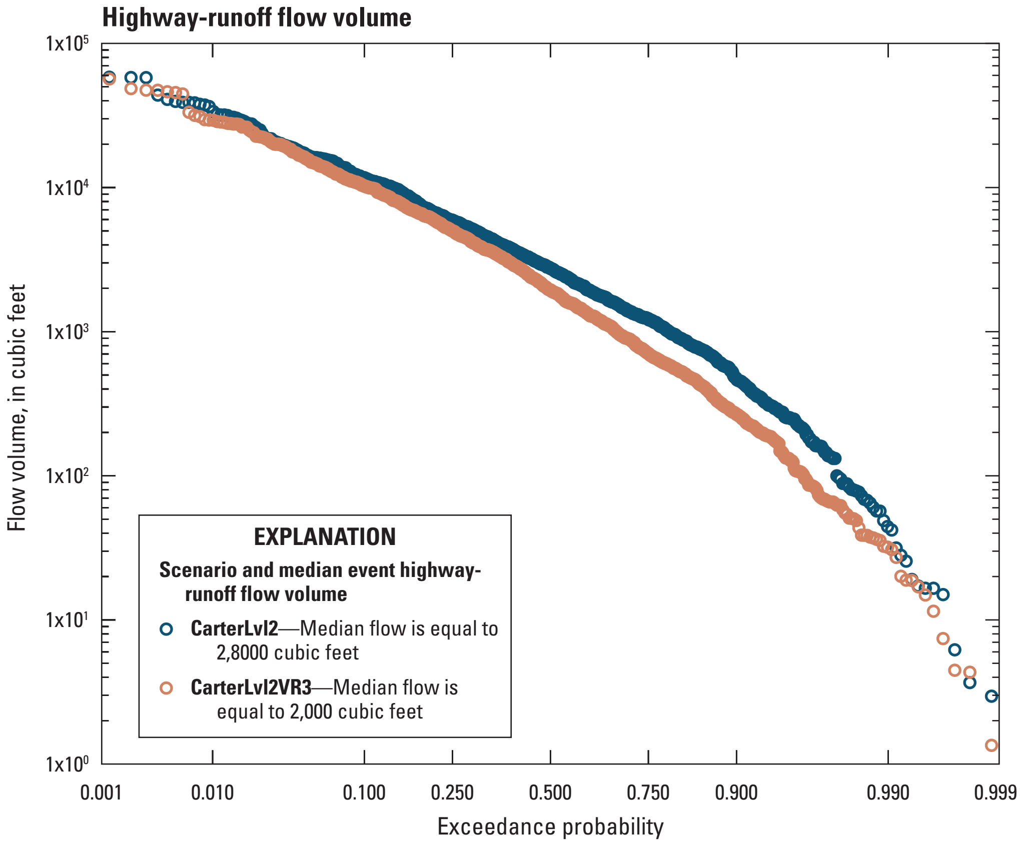


Figure 39. Exceedance probabilities of highway-runoff volumes under scenarios 2 (CarterLvl2) and 3 (CarterLvl2VR3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Mean and median upstream and highway-runoff EMCs of chloride were identical for scenarios CarterLvl2 and CarterLvl2VR3 (fig. 40) because the upstream and highway-runoff concentration statistics were identical between the two scenarios. Median downstream EMCs of chloride were slightly lower for CarterLvl2VR3 than CarterLvl2. This small difference is the result of there being slightly more highway runoff for CarterLvl2 at lower exceedance probabilities (fig. 39), resulting in less dilution of highway runoff than was observed for CarterLvl2VR3. The difference in mean EMCs of chloride between CarterLvl2 and CarterLvl2VR3 was greater than the difference in median, with CarterLvl2VR3 once again having a lower value than CarterLvl2.

EMCs of chloride were consistent between the two scenarios at most exceedance probabilities (fig. 41). Both scenarios achieved the study criterion for chloride (1 percent of event EMCs exceeded 860 mg/L). These results show that at the Carter Creek Branch 1 study site, the use of local (level-3) volumetric runoff coefficients results in little difference in event EMCs for most exceedance probabilities.

The probability plots of annual concurrent runoff loads of chloride for scenarios CarterLvl2 and CarterLvl2VR3 have similar slopes (fig. 42) and are relatively consistent at most exceedance probabilities. The median annual concurrent runoff loads were equal for both simulations (5,100 pounds). These results suggest that because the calculated local volumetric runoff coefficients are close to those provided by the national equations, the use of local volumetric runoff coefficients does not result in substantial changes to downstream EMCs, exceedance probabilities, or annual concurrent runoff loading estimates.

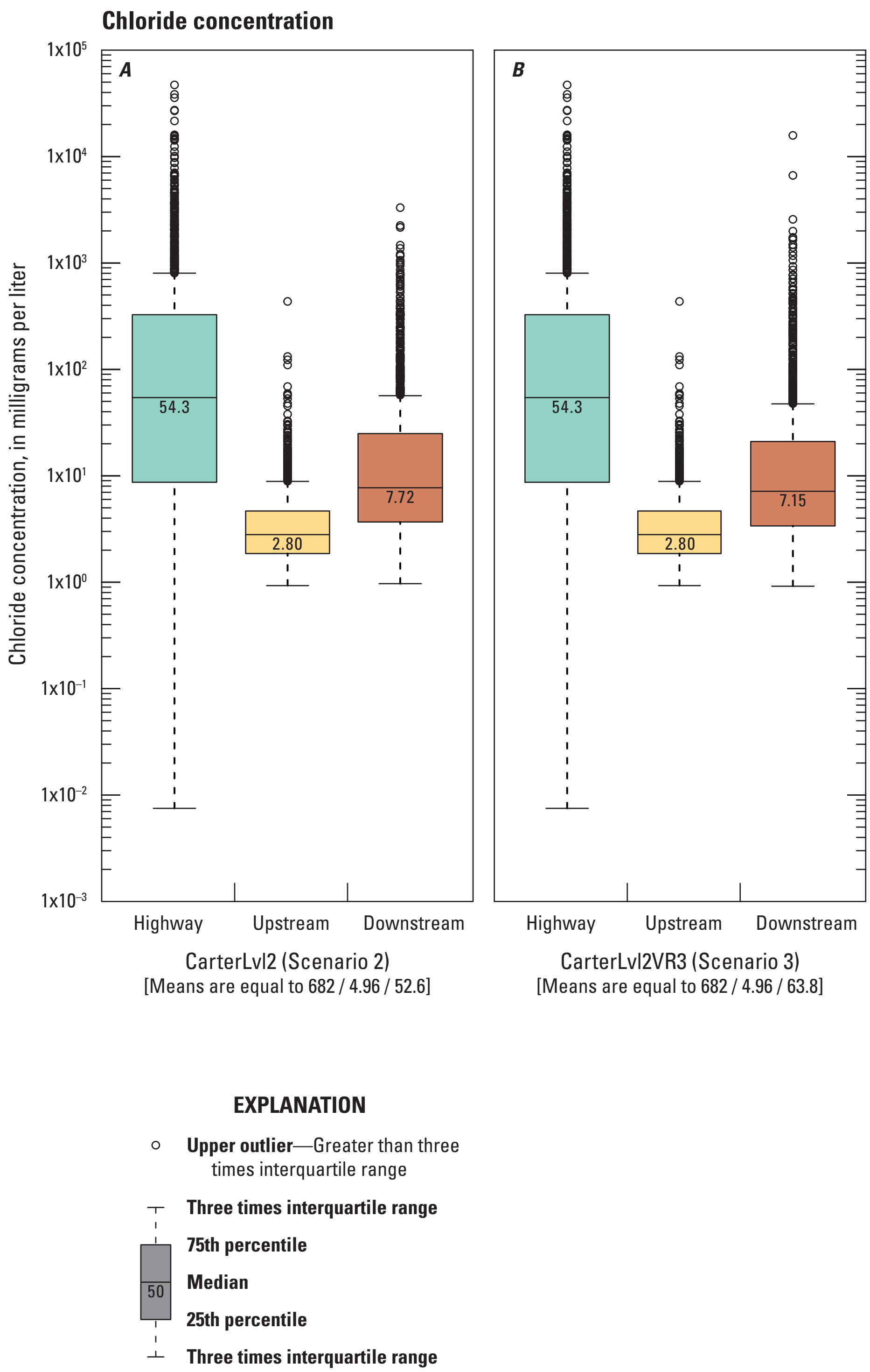


Figure 40. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 2 (CarterLvl2) and (*B*) 3 (CarterLvl2VR3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

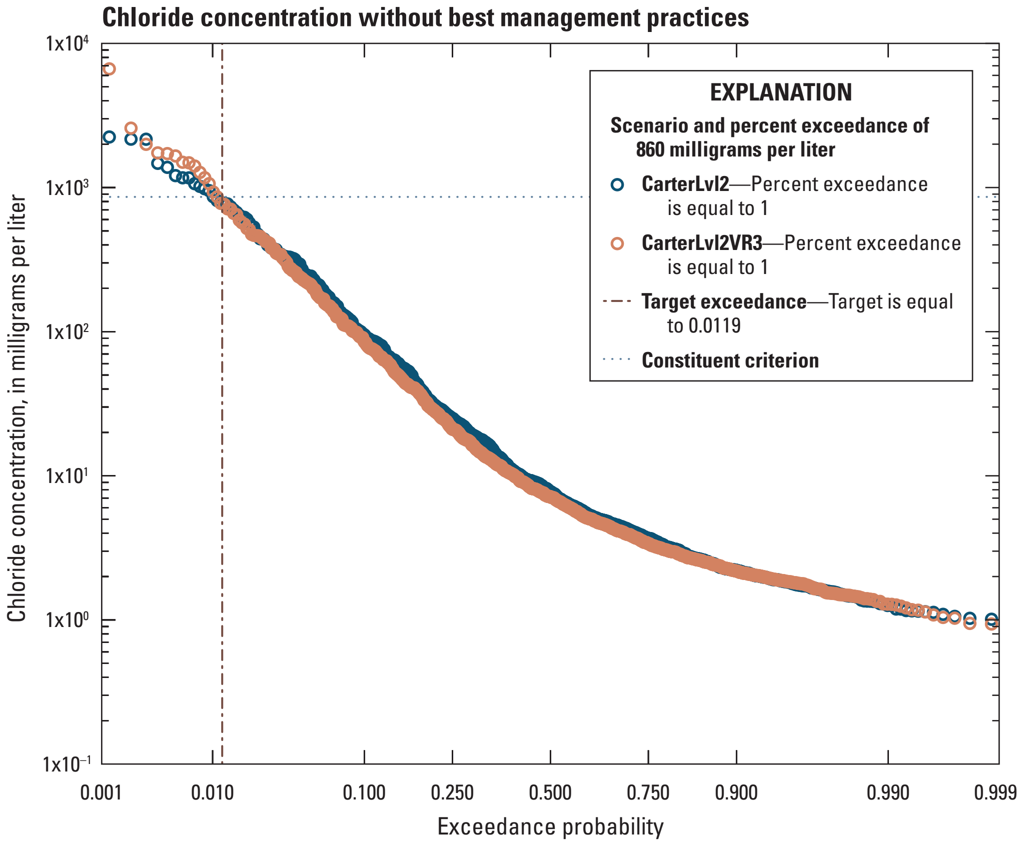


Figure 41. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 2 (CarterLvl2) and 3 (CarterLvl2VR3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

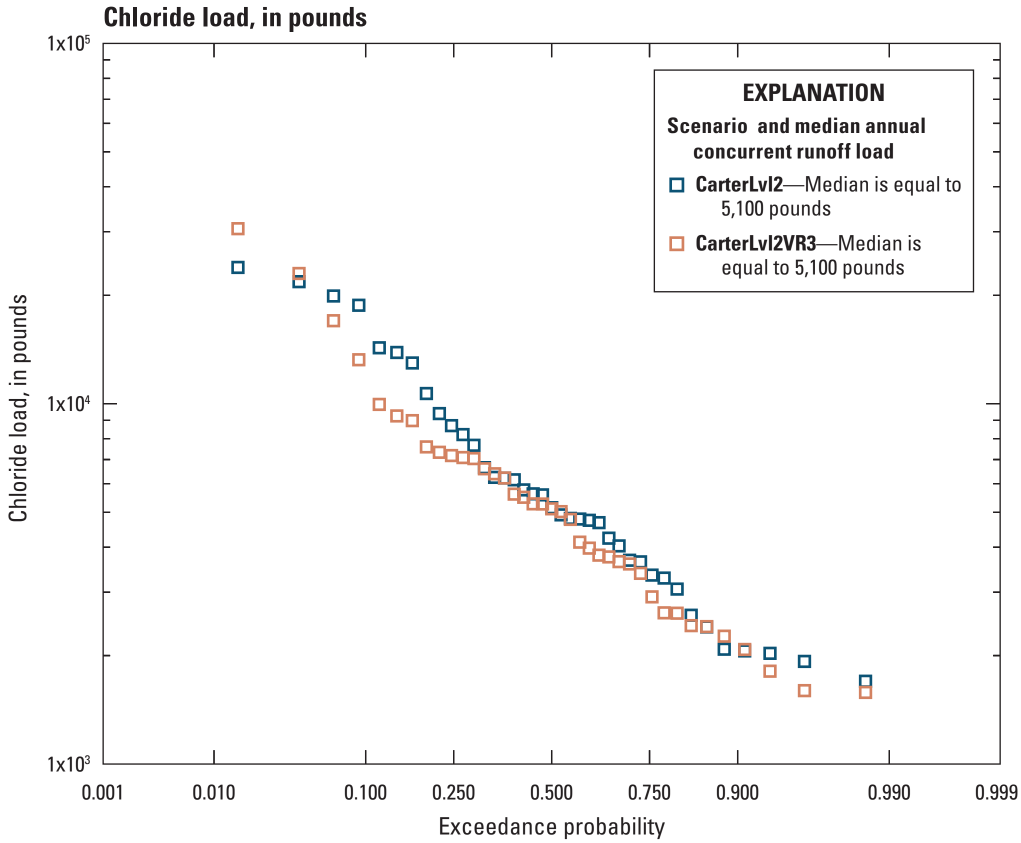


Figure 42. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 2 (CarterLvl2) and 3 (CarterLvl2VR3) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Best Management Practices Scenario

In addition to the SELDM scenarios developed for sensitivity analyses, scenario 12 (“CarterLvl3BMP”) was developed to evaluate the use of best management practices (BMP) on the distribution of chloride in the Carter Creek watershed. A BMP that removes chloride from highway runoff would be cost-prohibitive and unrealistic for application to highway runoff. Consequently, the BMP modeled in CarterLvl3BMP used only a hydrograph extension (an increase in the duration of highway runoff into the intersecting stream) to alter the chloride distribution. With the exception of the use of the BMP, CarterLvl3BMP was identical to CarterLvl3 (the level-3 analysis). By using the level-3 analysis as a baseline for comparison, the results from CarterLvl3BMP demonstrated the best estimate of what effect the hydrograph extension BMP would have on chloride distribution. The BMP statistics used in SELDM were the median hydrograph extension statistics from Granato (2014; table 3). For the SELDM hydrograph-extension inputs, the medians for the lower bound of the most probable value, upper bound of the most probable value, and minimum value were zero; the median maximum value was 18; and the median Spearman’s correlation coefficient was 0.45 (see Granato, 2013, for a full explanation of these terms).

The hydrograph extension resulted in a decrease in the average dilution factor (more dilution of the highway runoff) compared to CarterLvl3 (fig. 43). However, the decrease in the dilution factor did not result in a substantial change in downstream EMCs of chloride (fig. 44) nor in the annual concurrent runoff loading of chloride (not shown). The results suggest that the use of a hydrograph-extension BMP may result in a slight (less than 1-percent) decrease in peak chloride concentrations downstream, but that overall EMCs and annual concurrent runoff loading are unaffected in these simulations.

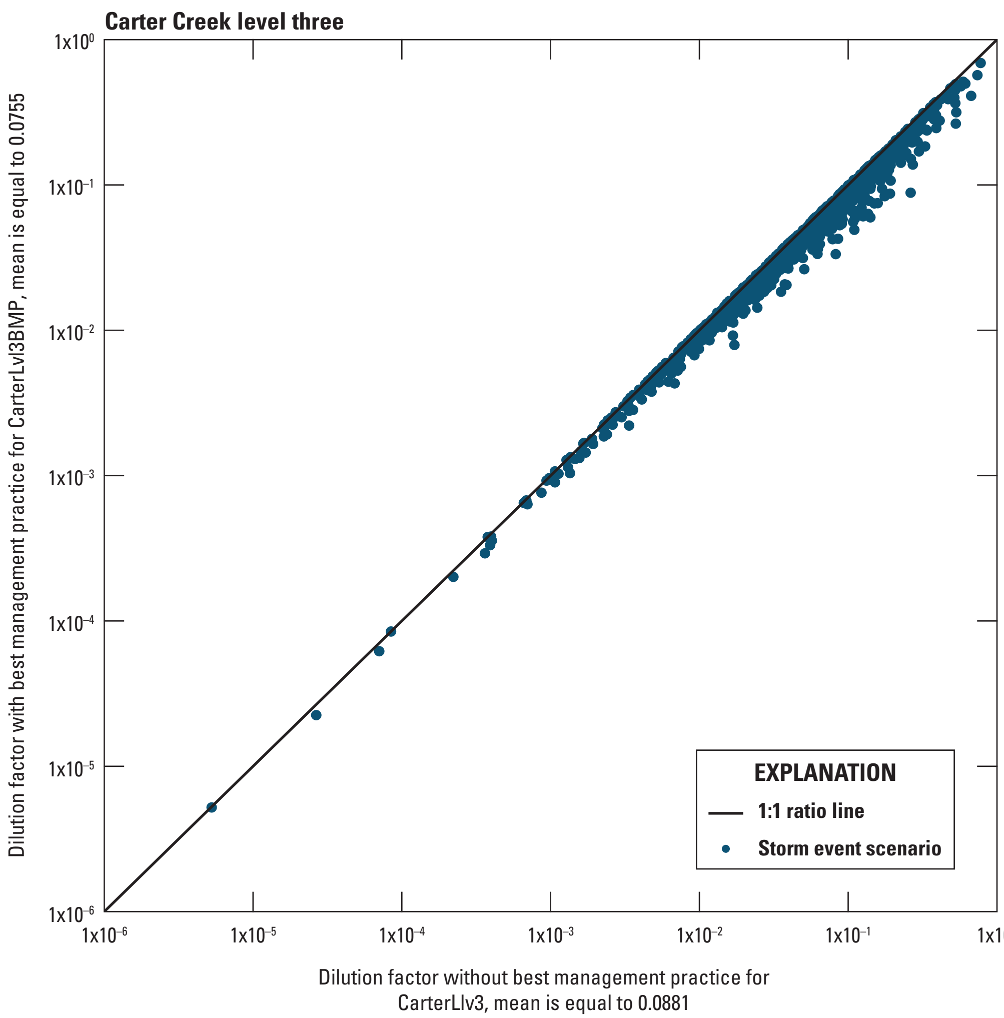


Figure 43. Dilution factors at the Interstate Route 5 (I–5) crossing under scenarios 11 (CarterLvl3) and 12 (CarterLvl3BMP) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

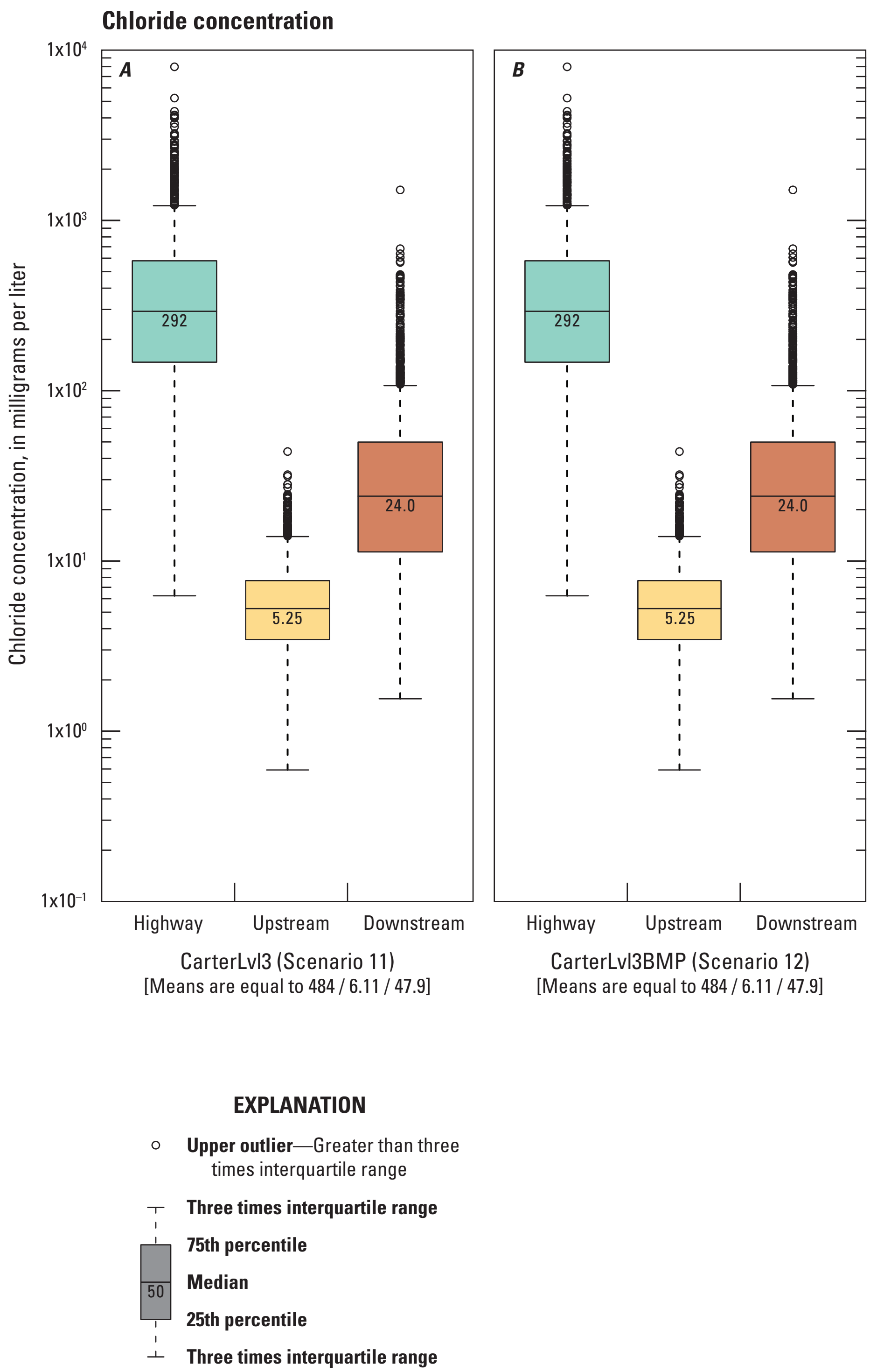


Figure 44. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 11 (CarterLvl3) and (*B*) 12 (CarterLvl3BMP) at Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

Wall Creek

Fewer simulations were run for Wall Creek because few data were collected at that location compared to Carter Creek. Consequently, many of the statistics derived for Carter Creek were directly transferred for use in the Wall Creek simulations. Although these data are not local (the data are from different watersheds), the Carter and Wall Creek watersheds were surmised to be geographically and characteristically similar enough that these data represent conditions closer to local than could be expected from most regional data analyses and were considered local for purposes of this study.

Scenario 13 (designated "WallLvl1") assumed no local or regional data were available for Wall Creek with the exception of the regional highway-runoff and upstream chloride concentrations (see section, "Estimation of Water-Quality Statistics"). Regional chloride data were included because use of national statistics without such data would have resulted in an extreme underestimation of chloride EMCs; many of the highway-runoff statistics are generated from low- locations without the regular application of deicers. Because deicing operations have a unique water-quality signature resulting from application of large masses of water-quality constituents directly onto the pavement, it is important to select datasets that represent conditions for many storm events over the entire year, including wide variations in normal and deicing conditions. The effects of deicing may persist in runoff because deicing chemicals leach from the pavement after seasonal use of deicers has ceased (Granato and Smith, 1999; Smith and Granato, 2010). Many highway-runoff monitoring studies in the Highway-Runoff Database (Granato, 2019) have few storms and, because of the difficulties involved in the collection of runoff water-quality data under freezing conditions, do not represent the full range of seasonal conditions. These limitations may not be critical for many highway-runoff water-quality constituents but are an important consideration for selecting datasets to represent deicing-chemical concentrations.

Scenario 14 (labeled as "WallLvl3") used all available local data, and regional data when local data were not available (table 3). WallLvl3 should provide the most representative estimates of chloride distribution in the Wall Creek watershed.

Highway EMCs of chloride differed substantially between scenarios WallLvl1 and WallLvl3 (figs. 45 and 46). WallLvl3 estimated a substantially larger median highway-runoff EMC of chloride than WallLvl1, but a smaller mean and less variability. Mean and median upstream EMCs of chloride were similarly small for both scenarios, with EMCs from WallLvl3 being the larger of the two. Relative to WallLvl1, mean and median downstream EMCs of chloride were higher for WallLvl3. WallLvl1 had more variability and higher levels of skewness in the population of upstream EMCs because national and regional data were used. This higher level of skewness is also evident in the ratio of mean to median downstream EMCs of chloride. For WallLvl1, the mean EMC was about six times higher than the median, whereas for WallLvl3 the same ratio was close to two.

The difference in downstream chloride EMC variability between the two scenarios is evident in the plot of exceedance probabilities (fig. 46). WallLvl1 had substantially more variability than WallLvl3, with higher EMCs at low exceedance probabilities and lower EMCs at higher exceedance probabilities. Both scenarios met the study chloride criterion of having fewer than 1.19 percent of EMCs above the 860 mg/L CMC.

Use of only level-1 analyses in WallLvl1 resulted in a substantial overestimation of upstream flow for all exceedance probabilities (fig. 47) and overestimation of highway runoff at low exceedance probabilities (high flows; fig. 48) compared to WallLvl3. Consequently, annual concurrent runoff loads of chloride were substantially higher for WallLvl1 than for WallLvl3 at low exceedance probabilities (fig. 49). Conversely, the extra streamflow had less effect at high exceedance probabilities (low flows), resulting in annual concurrent runoff loads that were higher for WallLvl3 than for WallLvl1. These results suggest that the use of only default and level-1 SELDM analyses at Wall Creek would result in a substantial overestimation (relative to WallLvl3) in the variability of annual concurrent runoff loads of chloride, driven primarily by overestimation of upstream flow and highway runoff at low exceedance probabilities.

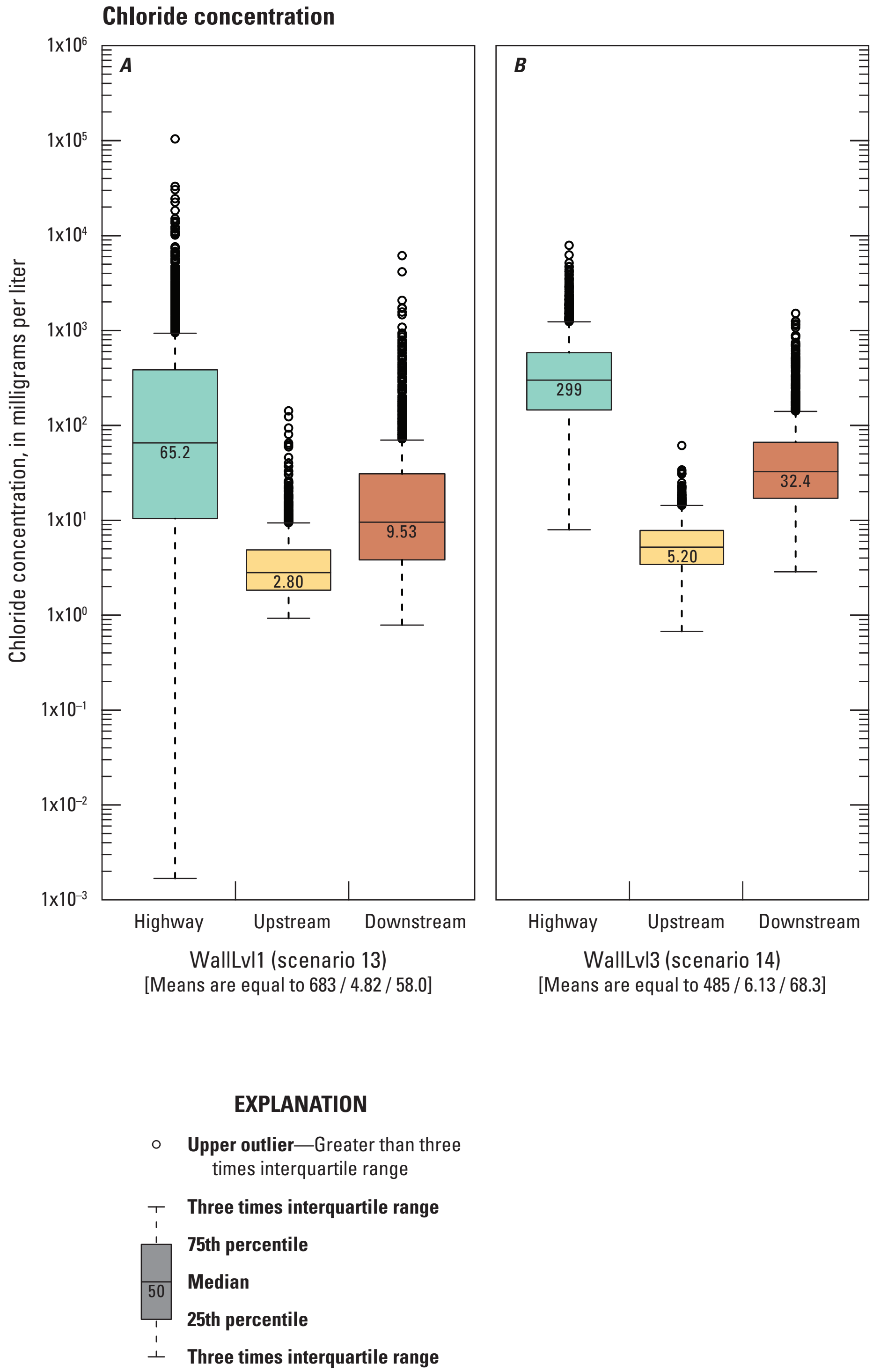


Figure 45. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 13 (WallLvl1) and (*B*) 14 (WallLvl3) at Wall Creek in the Siskiyou Pass, southern Oregon.

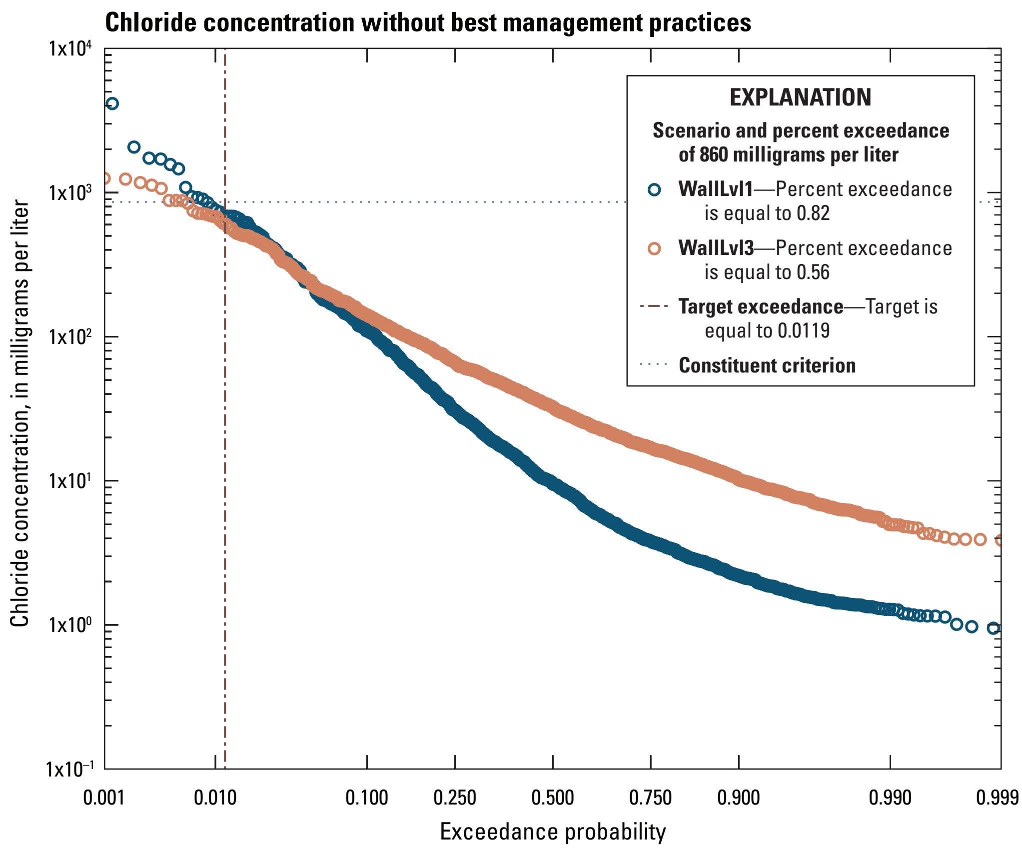


Figure 46. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 13 (WallLvl1) and 14 (WallLvl3) at Wall Creek in the Siskiyou Pass, southern Oregon.

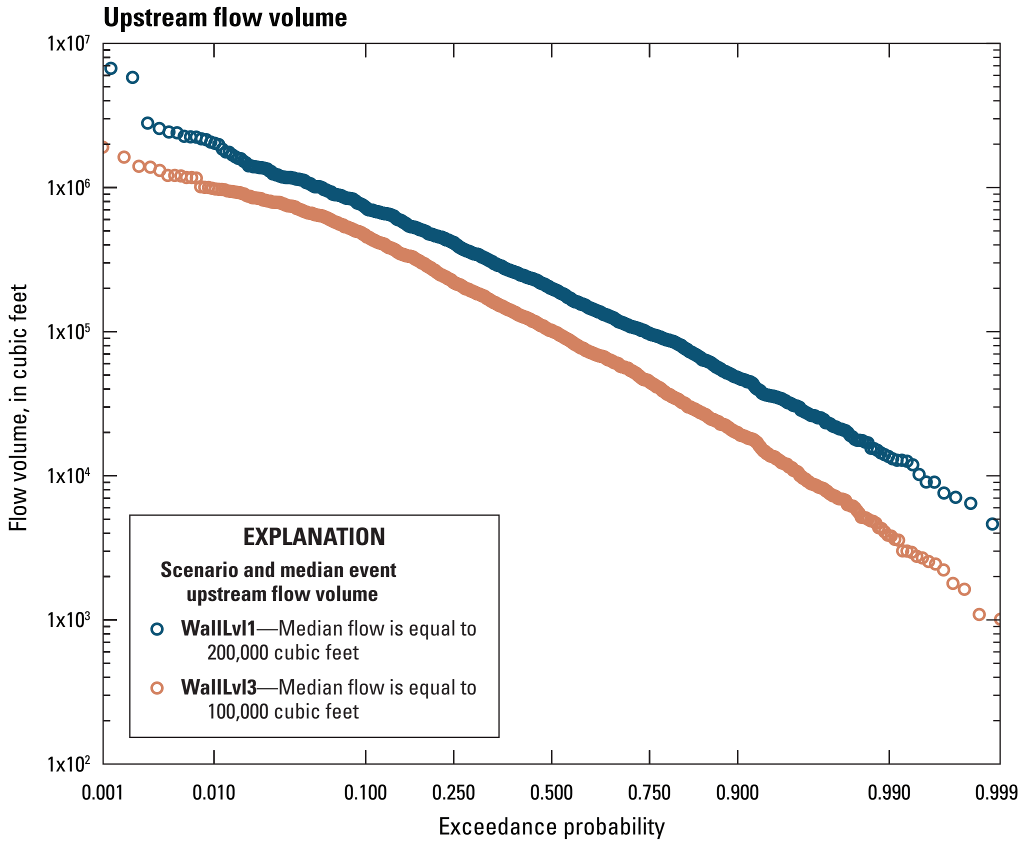


Figure 47. Exceedance probabilities of stormflow volumes under scenarios 13 (WallLvl1) and 14 (WallLvl3) at Wall Creek in the Siskiyou Pass, southern Oregon.

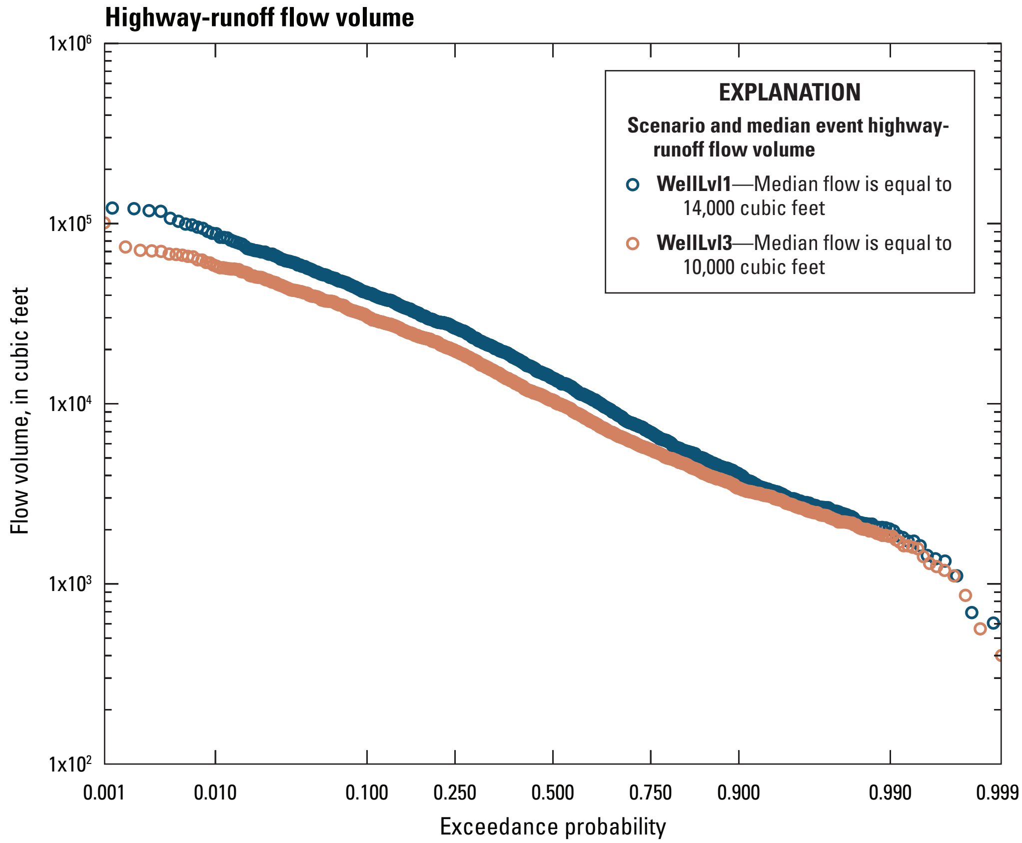


Figure 48. Exceedance probabilities of highway-runoff volumes under scenarios 13 (WallLvl1) and 14 (WallLvl3) at Wall Creek in the Siskiyou Pass, southern Oregon.

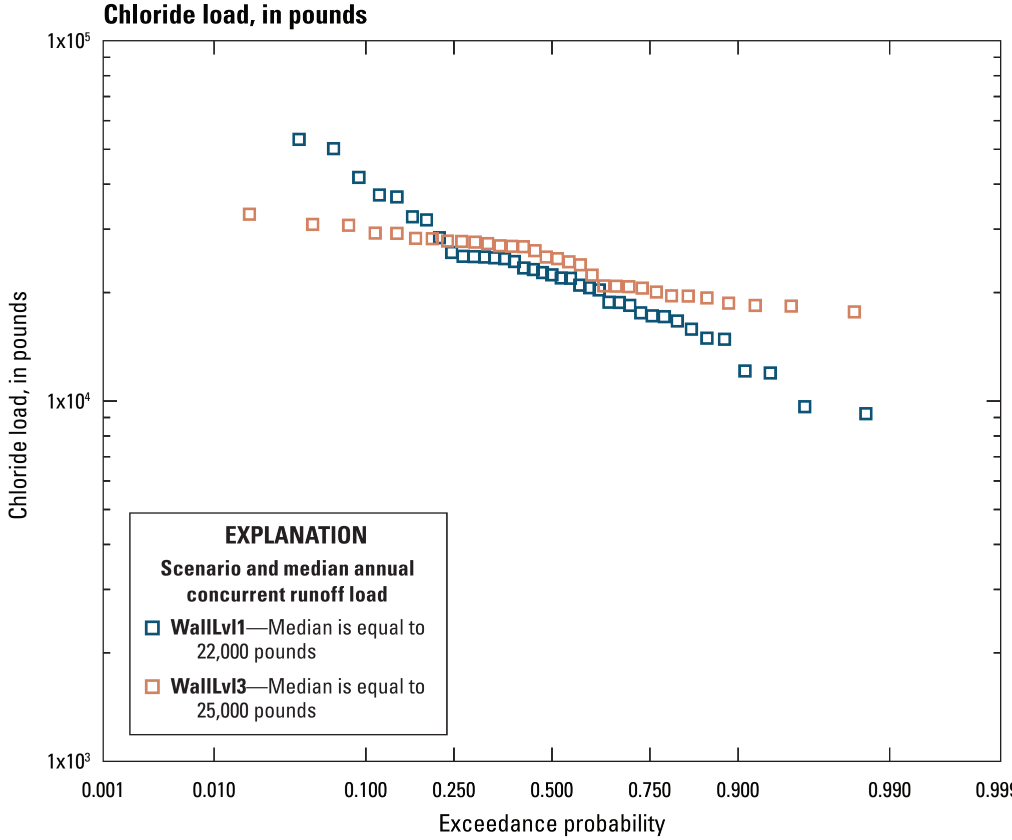


Figure 49. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 13 (WallLvl1) and 14 (WallLvl3) at Wall Creek in the Siskiyou Pass, southern Oregon.

Carter Creek, Branch 6

One level-3 simulation at Carter Creek Branch 6 was developed to study the effects of the I–5 crossing with Carter Creek downstream from Branch 1 (scenario 15, designated “GrCarterLvl3” [The “Gr” is an abbreviation for “greater” Carter Creek]). Inputs to this scenario were identical to those for scenario 11 (Carter Creek Branch 1 level-3 analysis CarterLvl3) except for highway hydraulic variables and upstream basin characteristics.

For this scenario, Oregon State Route 273 was not considered because it does not receive as much deicer chloride application as I–5, and no runoff chloride-concentration data were available from the highway. The highway catchment size was increased to reflect the longer length of I–5 that passes through the larger drainage area of Branch 6 (fig. 1). For reference, the percentage increase in highway catchment size between Branch 1 and Branch 6 was smaller (increase of about 51 percent) than the percentage increase in upstream drainage area (about 136 percent). Consequently, the proportion of drainage from highway runoff was less for Branch 6 simulations than for the simulations at Branch 1. Travel time between I–5 and the analysis point at USGS station 14348430 near Oregon State Route 273 was not considered because slopes for this watershed are high and distances are short, suggesting that time of travel between I–5 and USGS station 14348430 is negligible.

Upstream basin characteristics were updated from CarterLvl3 to reflect the larger watershed. Streamflow statistics were not updated because all variables are entered in cubic feet per second per square mile, so the streamflow parameters scale with the larger drainage area. The percentage of upstream impervious area was consistent between the two scenarios (within 1.3 percent), suggesting volumetric runoff coefficients should be similar, so these values also were not changed.

The increase in highway catchment area resulted in an increase in estimated highway runoff from CarterLvl3 to GrCarterLvl3 (median runoff volume increase of about 180 percent; fig. 50). A smaller increase occurred for upstream streamflow (median upstream streamflow volume almost doubled; fig. 51). Upstream and highway-runoff EMCs were identical between the two scenarios because input variables were identical (fig. 52). Downstream EMCs were slightly larger for GrCarterLvl3, which is a result of GrCarterLvl3 having a larger dilution factor (not pictured).

The resulting rates of exceedance of the chloride CMC were similar for GrCarterLvl3 and CarterLvl3, with few of the simulations exceeding the 860 mg/L CMC (fig. 53)[2]. Similar, small increases in CMC exceedances from CarterLvl3 to GrCarterLvl3 were seen with magnesium and sodium, with exceedance probabilities increasing from 0.062 percent to 0.37 percent, and 20 percent to 25 percent, respectively (not shown).

The exceedance rate of the chloride CMC was one of the few simulation statistics that can be compared against collected data. At USGS station 14348430, the chloride CMC was exceeded 4 times in 112 events, an exceedance rate of 3.6 percent. In absolute terms (as opposed to relative terms), this rate of exceedance is within reasonable limits of the modeled exceedance rate (0.062 percent). However, the odds of having 4 CMC exceedances in 112 events with a probability of exceedance of 0.062 percent is below 1 percent. In other words, it is statistically likely that the modeled rate of CMC exceedance is lower than the actual rate (>99 percent). This level of uncertainty in the simulated results for GrCarterLvl3 is expected given the need to extrapolate much of the SELDM input data from Branch 1 to Branch 6. Limitations of the modeling are further discussed in section, "Limitations of the Analyses."

The median increase in annual concurrent runoff load of chloride between scenarios CarterLvl3 and GrCarterLvl3 was about 13,500 pounds per year, representing an increase of about triple the annual load (factor of 2; fig. 54). Median annual concurrent runoff loads increased by a factor of about 2.3 for magnesium (fig. 55) and 2.4 for sodium (not shown). Given the uncertainty of the Branch 6 model (fewer local data available than for Branch 1), the difference between factors of 2.3 and 2.8 is not substantial. Therefore, the increases in the three constituents between scenarios can be considered essentially consistent.

Findings from GrCarterLvl3 demonstrate that the relative increase in percentage contribution from highway runoff (table 25) results in higher levels of dilution in downstream flows, further resulting in slightly larger EMCs and a slightly larger frequency of CMC exceedances. Downstream annual concurrent runoff loads are larger, the amount of increase also being a function of the ratio of water-quality constituent loading being sourced from highway deicer application to the constituent being sourced from upstream.

[2]For all probability plots, exceedance probabilities range from 0.001 (0.1 percent) to 0.999 (99.9 percent). The three instances for scenario GrCarterLvl3 in which the EMCs were simulated above the CMC of 860 mg/L of chloride do not appear on figure 53 (a larger range of probability values would be needed to view all results). Figure 53 was not replotted with a greater range of exceedances to maintain consistency with previous figures.

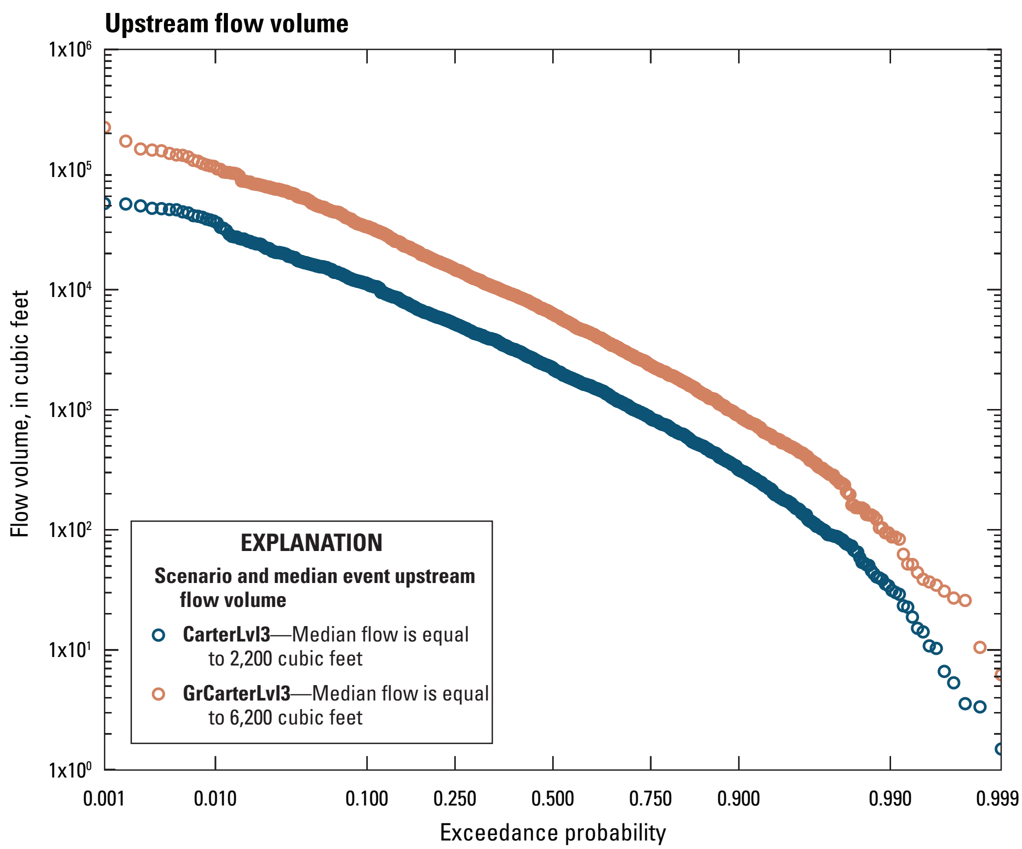


Figure 50. Exceedance probabilities of highway-runoff volumes under scenarios 11 (CarterLvl3) at Carter Creek Branch 1 and 15 (GrCarterLvl3) at Carter Creek Branch 6 in the Siskiyou Pass, southern Oregon.

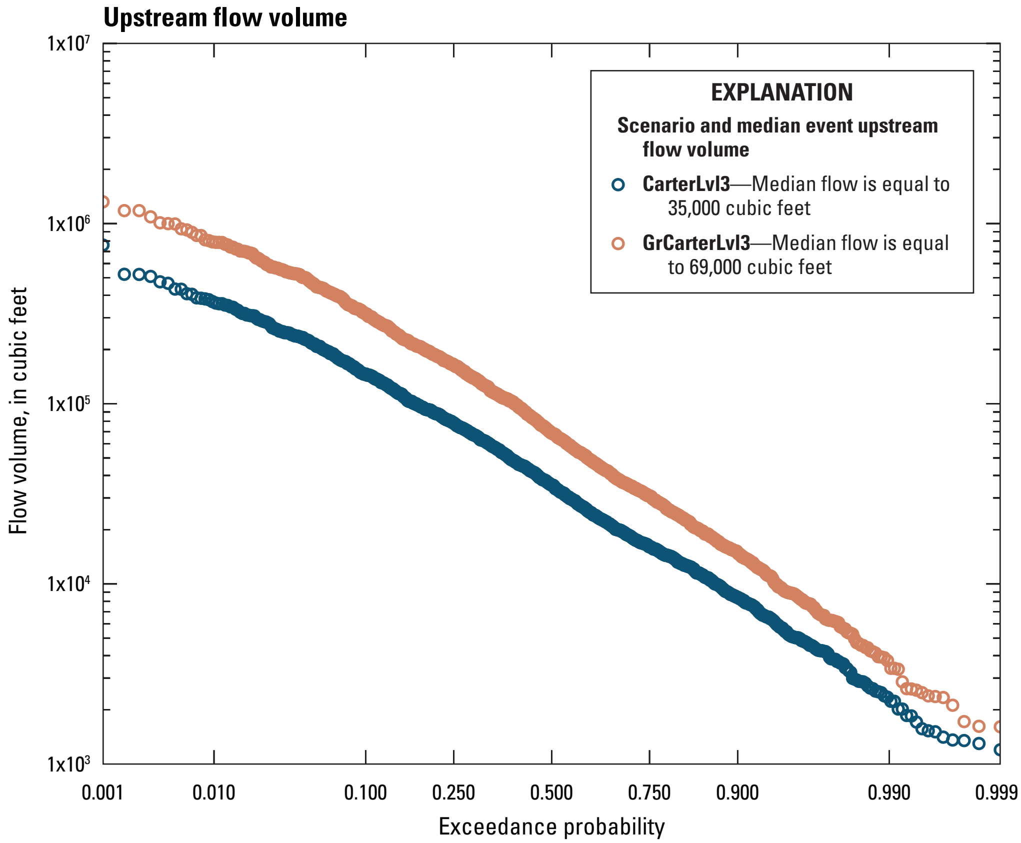


Figure 51. Exceedance probabilities of stormflow volumes under scenarios 11 (CarterLvl3) at Carter Creek Branch 1 and 15 (GrCarterLvl3) at Carter Creek Branch 6 in the Siskiyou Pass, southern Oregon.

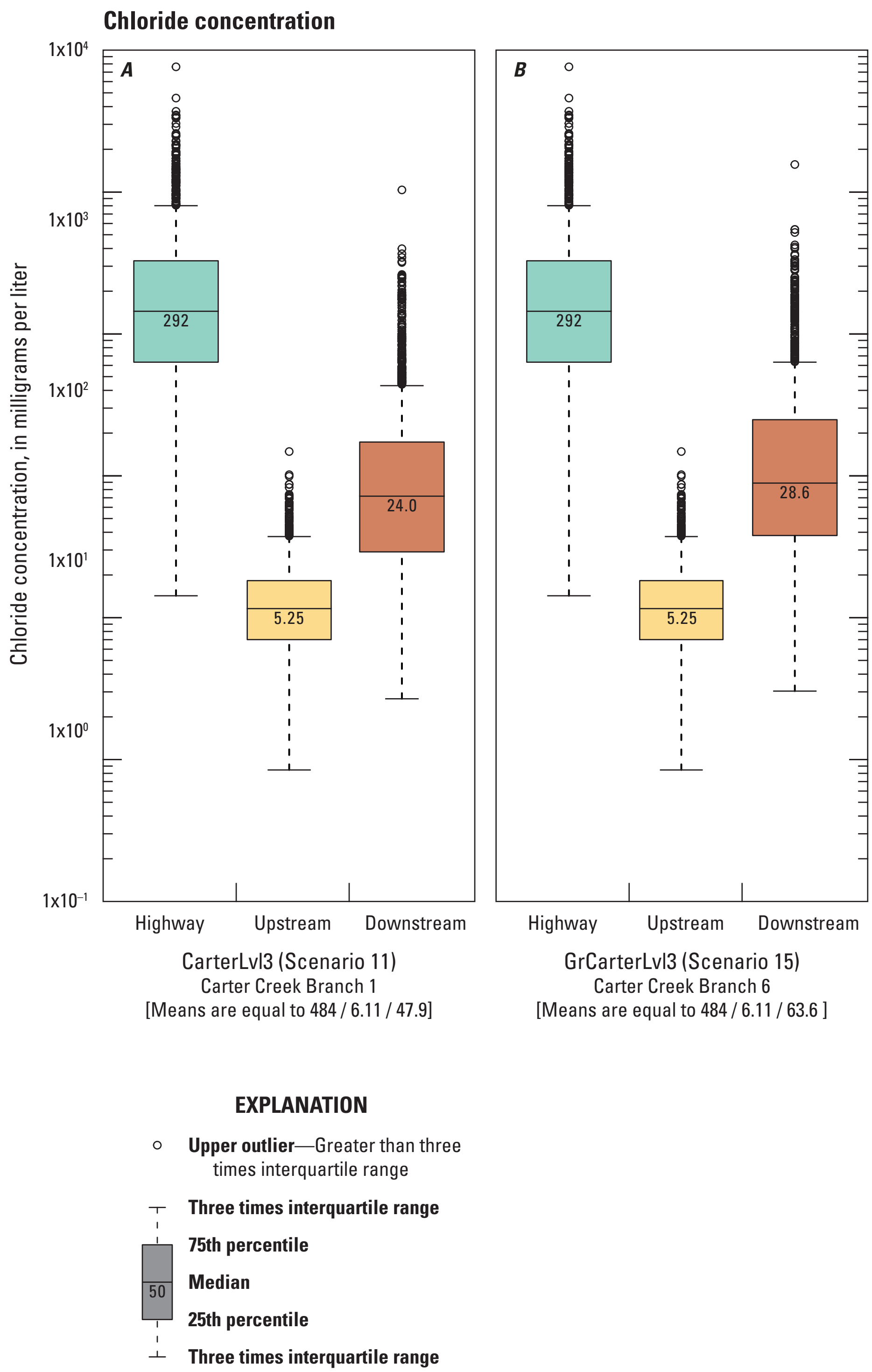


Figure 52. Highway-runoff, upstream, and downstream event mean concentrations of chloride for scenarios (*A*) 11 (CarterLvl3) at Carter Creek Branch 1 and (*B*) 15 (GrCarterLvl3) at Carter Creek Branch 6 in the Siskiyou Pass, southern Oregon.

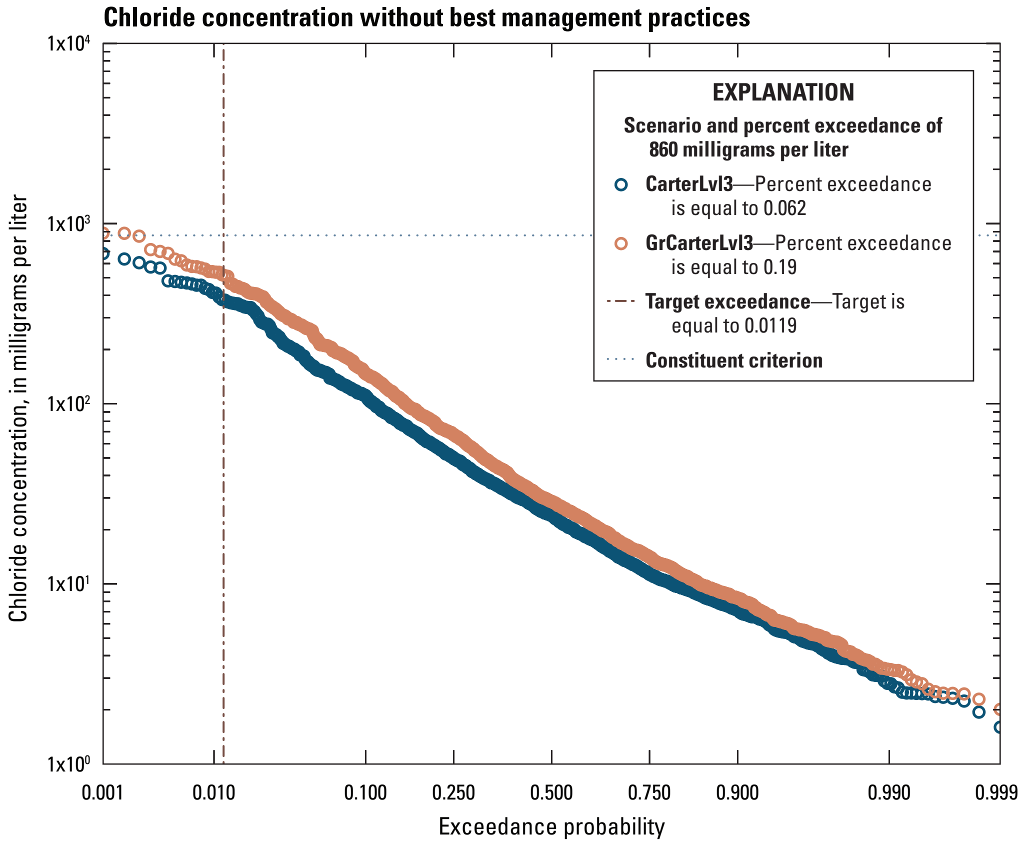


Figure 53. Exceedance probabilities of downstream event mean concentrations of chloride under scenarios 11 (CarterLvl3) at Carter Creek Branch 1 and 15 (GrCarterLvl3) at Carter Creek Branch 6 in the Siskiyou Pass, southern Oregon.

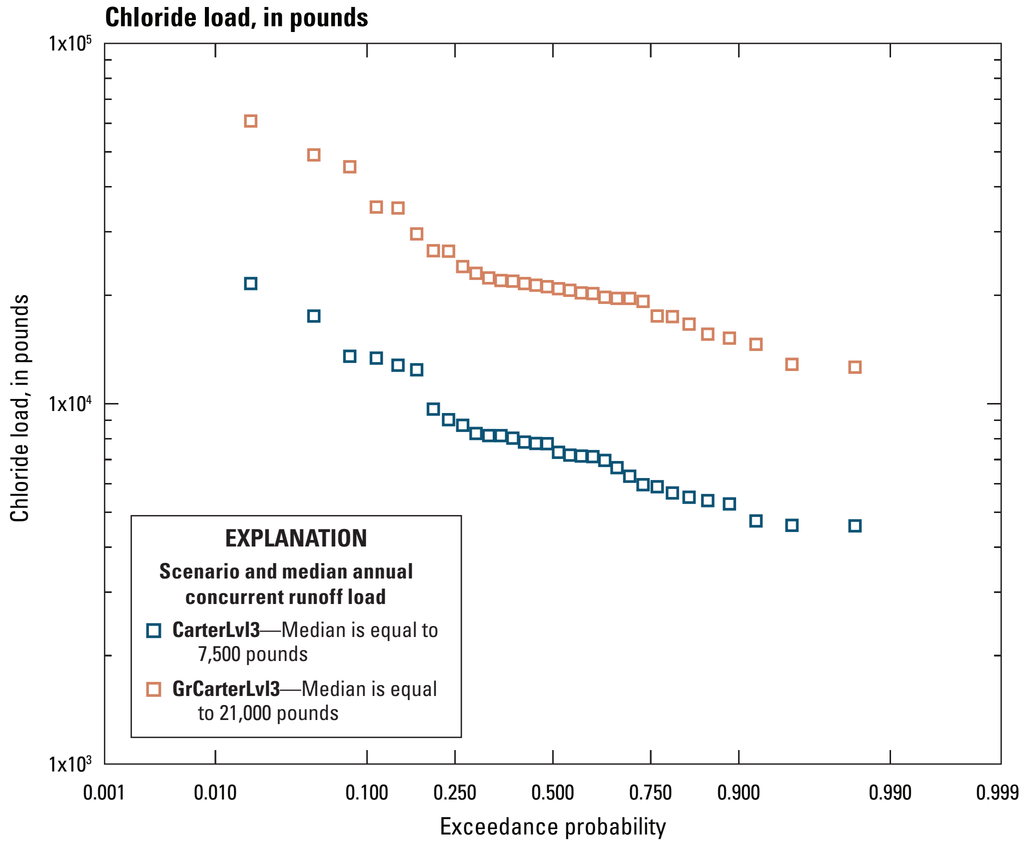


Figure 54. Exceedance probabilities of annual concurrent runoff loads of chloride under scenarios 11 (CarterLvl3) at Carter Creek Branch 1 and 15 (GrCarterLvl3) at Carter Creek Branch 6 in the Siskiyou Pass, southern Oregon.

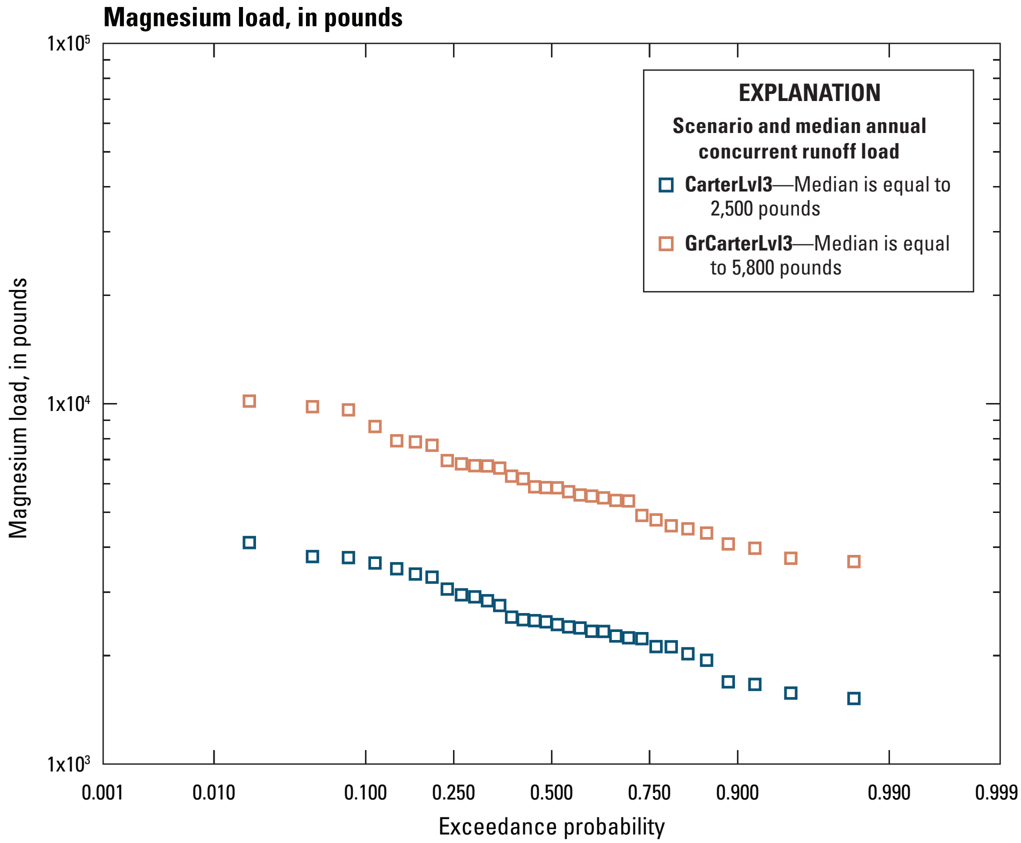


Figure 55. Exceedance probabilities of annual concurrent runoff loads of magnesium under scenarios 11 (CarterLvl3) at Carter Creek Branch 1 and 15 (GrCarterLvl3) at Carter Creek Branch 6 in the Siskiyou Pass, southern Oregon.

Table 25. Percentage of annual concurrent runoff chloride load represented by highway runoff for SELDM scenarios 11 (CarterLvl3) and 15 (GrCarterLvl3) in the Siskiyou Pass, southern Oregon.

Scenario number	Scenario name	Highway-runoff chloride concentrations	Chloride load (percent)
11	CarterLvl3	Local	87.4
15	GrCarterLvl3	Local	79.1

Sensitivity Analysis Findings

To compare the relative value of local data collection to define individual parameter inputs against the value of using regional data to define inputs, the values from scenario 2 (CarterLvl2) and 11 (CarterLvl3) were compared against each sensitivity analysis (table 26). Scenario results for highway-runoff, upstream, and downstream EMCs were compared between model simulations, as were simulated exceedance rates of CMCs and annual concurrent highway-runoff and downstream constituent loading. In this manner, the effects of adding local data from any one source (flow, precipitation, highway-runoff EMCs, upstream EMCs, or volumetric runoff coefficients) or removing regional data can be compared.

Results were evaluated against CarterLvl3 (scenario 11), which was developed using the maximum amount of local data and is considered the scenario most likely to have produced the best estimates, by calculating the percentage difference between the scenario of interest and the results from CarterLvl3 (that is, percentage differences shown in table 26 were calculated relative to the results from CarterLvl3). In some instances, scenarios with the inclusion of local data produced results that were more divergent from CarterLvl3 than the results from CarterLvl2 (scenario 2,which was simulated using all regional data). For example, results from CarterLvl2 show an estimated upstream chloride EMC of 4.96 mg/L, which is about 19– percent less than the CarterLvl3 estimate of 6.11 mg/L. The addition of local precipitation data to CarterLvl2 (scenario 5, CarterLvl2Pcp3) resulted in an upstream chloride EMC of 4.75 mg/L, which is about 22 percent less than the CarterLvl3 estimate. This does not imply that the addition of a particular form of local data, such as local precipitation in this case, would provide less-representative results. Although the addition of any one local dataset may result in values that are less similar to those

Table 26. Results from Stochastic Empirical Loading and Dilution Model (SELDM) sensitivity analyses, scenarios 2–11, Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

[Table 26 (in the form of Microsoft Excel and .csv files) is available for download at https://doi.org./10.3133/sir20225091.]

from CarterLvl3, the addition of all local datasets should result in the most representative input. As such, the addition of a set of local data is more likely to result in improved estimates than not.

Mean highway-runoff and upstream EMC outputs were sensitive only to local highway-runoff and upstream water-quality constituent concentration data. The addition of precipitation, streamflow, and runoff-coefficient local data resulted in no or minimal effect on final EMC values. This was because the population of EMCs are directly simulated from the population-statistic inputs used in SELDM.

Mean downstream EMC values were affected by all local data but were most sensitive to the addition of local streamflow data. For CarterLvl2, the mean downstream EMCs of chloride were 10 percent higher than those from CarterLvl3. The addition of local streamflow data in CarterLvl2Q3 (scenario 7) resulted in downstream EMCs that were 42 percent larger than in CarterLvl3, a net increase of 32 percent relative to the CarterLvl2 results. The use of local streamflow data in the study basins resulted in substantially lower flows than regional estimates of streamflow. This decrease in streamflow resulted in a higher proportion of highway runoff in the channel downstream of the confluence with I–5, and consequently high receiving-water EMCs of chloride, because highway-runoff EMCs of chloride were much larger than upstream EMCs of chloride.

Local streamflow data had less effect on downstream EMCs of magnesium and sodium than on EMCs of chloride. This relative lack of effect was in large part owing to the ratio of mean upstream EMCs to highway-runoff EMCs. Whereas mean highway-runoff chloride EMCs were typically about two orders of magnitude higher than upstream chloride EMCs, the ratios of upstream to highway-runoff EMCs were much smaller for magnesium and sodium. Consequently, the proportion of downstream flow represented by highway runoff had a lesser effect on downstream EMCs. In other words, because the difference between upstream and highway-runoff EMCs was greater for chloride than for magnesium and sodium, the decrease in contribution from upstream (rather than highway) sources resulted in a smaller increase in downstream concentrations for magnesium and sodium. The net effects of local streamflow data on downstream EMCs of magnesium and sodium were within 1 percent.

Exceedance rates of the CMCs were generally small, which made analyzing the sensitivity of the exceedance rates to the introduction of local inputs difficult. For the study chloride CMC (860 mg/L), exceedance rates were most sensitive to the introduction of local highway EMCs of chloride. The CMC exceedance rates from the level-2 and level-3 analyses (scenarios CarterLvl2 and CarterLvl3, respectively) were about 1 percent and 0.06 percent, respectively. The introduction of local highway-runoff EMCs of chloride resulted in a CMC exceedance rate of zero (CarterLvl2HwyConcLvl3, scenario 10), which is a net change of 1 percent. For all other scenarios in which the addition of local data was simulated, net changes from CarterLvl2 were less than 0.5 percent. The same general findings were true for magnesium, which also had small CMC exceedance rates. The exceedance rate of the sodium CMC was most sensitive to the introduction of local streamflow data (CarterLvl2Q3, scenario 7), which changed the water-quality CMC exceedance rate from 18 percent (CarterLvl2) to 23 percent.

Annual loading of concurrent highway runoff of chloride was most sensitive to the addition of local precipitation data (CarterLvl2Pcp3, scenario 5). The addition of local precipitation data increased the mean annual loading of concurrent highway runoff from 4,700 (CarterLvl2) to 8,000 pounds of chloride. In relation to the level-3 analysis (CarterLvl3), loading calculated in CarterLvl2 was 25 percent less, whereas the loading of chloride in CarterLvl2Pcp3 was 27 percent more, a net change of 52 percent. CarterLvl2Pcp3 also estimated the largest change in annual concurrent highway-runoff loading relative to CarterLvl3 for magnesium (from –24 percent to +17 percent for a net change of 41 percent) and sodium (from –29 percent to +13 percent for a net change of 42 percent).

The introduction of local precipitation in CarterLvl2Pcp3 also produced the largest net percentage changes in annual concurrent runoff loading of chloride, magnesium, and sodium. This was expected given the proportion of downstream annual concurrent runoff loading that is sourced from the highway, especially for chloride. Net percentage changes from CarterLvl2 to CarterLvl2Pcp3 in relation to CarterLvl3 were 53 percent for chloride, 48 percent for magnesium, and 42 percent for sodium.

In summary, for Carter Creek Branch 1 EMCs were not only sensitive to the addition of local highway or upstream EMC data but also to the addition of local streamflow data. The exceedance rates for CMCs were most sensitive to local highway-runoff EMCs. Finally, mean annual concurrent highway-runoff and downstream loading were most sensitive to the addition of local precipitation data. The relative sensitivity of each input can be predicted based on (1) the magnitude of difference between local data and regional data used to derive inputs and (2) the dilution factor (proportion of downstream flow resulting from highway runoff) at the highway crossing. Table 27 summarizes the qualitative effects (specific to this study) of each local data source on three SELDM outputs.

Table 27. Qualitative ratings of effects of the inclusion of local data on various Stochastic Empirical Loading and Dilution Model outputs for Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon.

[EMC, event mean concentration; CMC, criterion maximum concentration]

Local data included	Qualitative effect		
	Downstream EMC	CMC exceedance	Mean annual concurrent runoff load
Precipitation	Low	Low	High
Upstream streamflow	High	Moderate–high	Low
Upstream concentrations	Moderate	Moderate	Low
Highway concentrations	Moderate–high	High	Low
Volumetric runoff	Moderate	Low	Low

Annual Constituent Loading

EMCs of chloride in runoff and meltwater from impervious areas that have been treated with chloride deicers and nearby pervious areas receiving plowed snow, highway runoff, splash, spray, or aerosols from paved areas are expected to be much greater than local background concentrations (for example, Howard and Haynes, 1993; Granato and Smith, 1999; Kunze and Sroka, 2004; Lundmark and Olofsson, 2007; Corsi and others, 2010a, 2010b; Smith and Granato, 2010). These greater concentrations were observed in the measured data from USGS stations 14348430, 420628122360400, and 420423122363100. Some deicer may be plowed or splashed off the highway and deposited onto roadside vegetation, infiltrate roadside soils, or be entrained in the atmosphere. Deicers that run off can enter soil water to be discharged as groundwater or stormwater at a later date. Deicers that dry on the road can later be mobilized by traffic and entrained in the atmosphere. As a result of these potential pathways, some applied road deicer will reach the stream, but other deicer will be “lost” from the watershed.

As part of this study, ODOT compiled chloride-deicer application information along I–5 during the winters of 2016–17 and 2017–18 (hereinafter referred to as 2017 and 2018, respectively; Jon Lazarus, Oregon Department of Transportation, written commun., 2019). For each application of NaCl or $MgCl_2$, ODOT drivers recorded the date and time of application, the pounds of NaCl or gallons of $MgCl_2$ applied per lane mile, the lanes on which the deicer was applied, the direction of travel (north or south), the total pounds or gallons used during a given application, the beginning and ending mile posts for where deicer was applied, and other information that could be used to ascertain the total amount of chloride deicer applied within the Carter and Wall Creek highway catchments. By comparing the amount of chloride, magnesium, and sodium applied within these watersheds, it is possible to estimate what percentages of those constituents are migrating to monitoring sites downstream from the highway.

Annual loads of chloride, magnesium, and sodium were calculated using the ODOT deicer application logs. For instances in which data entry was incomplete, a value was assigned based on the mean value of completed entries. For example, NaCl deicer application logs without the number of lanes documented were assigned a lane value of 1.62 based on the mean number of lanes for completed entries (1,301 entries of 2 lanes and 794 entries of 1 lane[3]).

Winter snowfall from 2018 was low compared to median values from 1991 to 2020 and compared to winter snowfall from 2017 and 2019 (fig. 56). Data from the Natural Resources Conservation Service show that peak SWE values for 2018 (11.9 inch the Big Red Mountain SNOTEL site; fig. 5), which is about 12 miles west of the Siskiyou Pass, were less than one-half of values recorded in the winters of 2017 (40.7 inches) and 2019 (31.0 inches), and that SWE values were low (less than 5 inches) in the winter of 2018 until late February (fig. 56).

Deicer application data were compared with highway runoff into Carter Creek Branch 1, streamflow data for Carter Creek Branch 6, and streamflow data for Wall Creek for the winter of 2018, which was a year of low snowpack relative to temporally adjacent winters (table 28). The Carter Creek Branch 6 highway-runoff water-quality constituent loading was computed by using the streamflow and specific conductance values from USGS station 420425122361700 and the specific conductance-chloride, specific conductance-magnesium, and specific conductance-sodium relations derived from the water-quality sampling completed at that site (table 15). The same approach was taken downstream at the Carter Creek Branch 6 site, using data from USGS station 14348430. For Wall Creek, specific conductance data from USGS station 420628122360400 were used. Because no streamflow data were available for this site, streamflow data from USGS station 14348430 were estimated using the drainage area ratio between the two sites. Relations between specific conductance and chloride, magnesium, and sodium from USGS station 14348430 were also used.

[3] $(1,301 \times 2 + 794 \times 1) / (1,301+794) = 1.62$

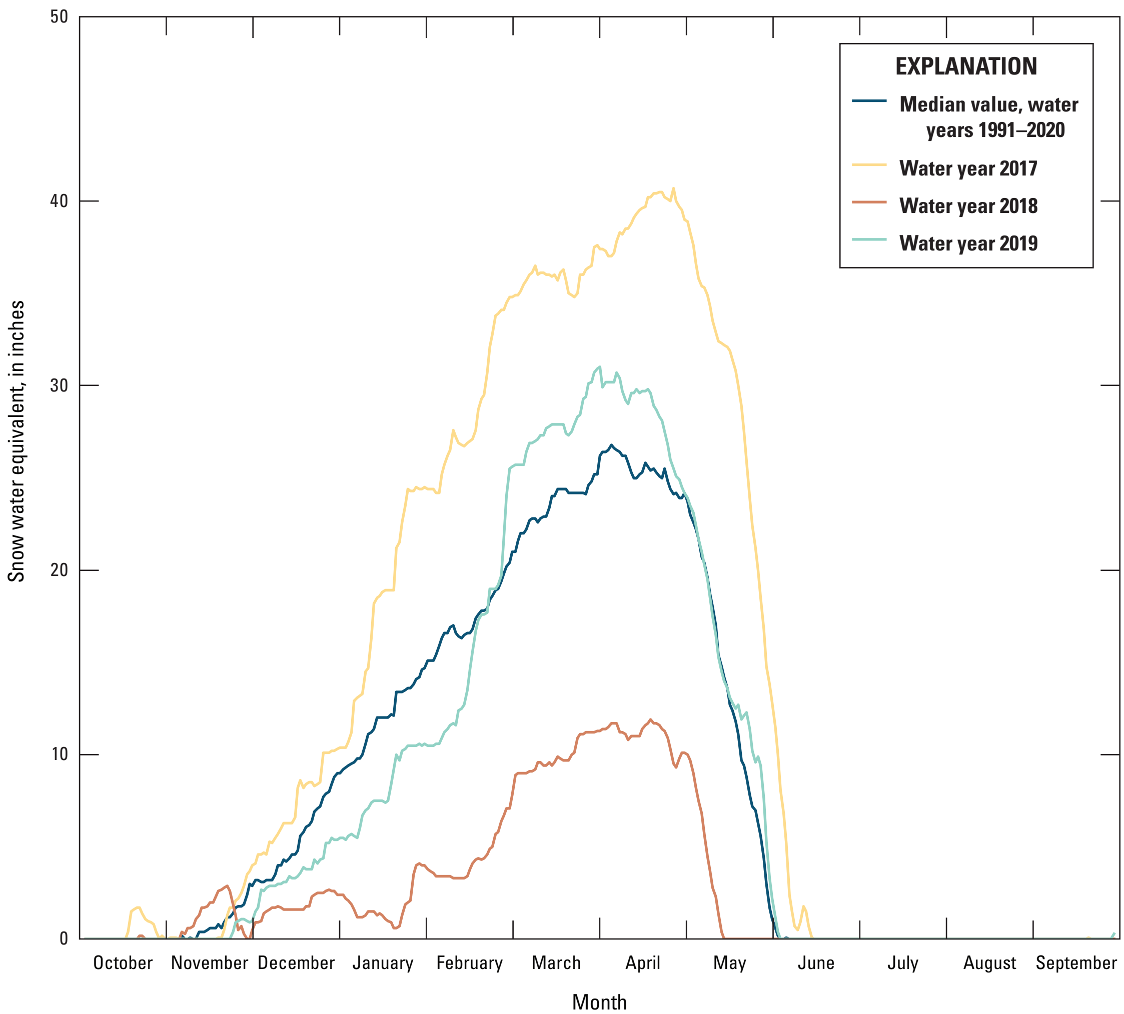


Figure 56. Snow water equivalent values from the Middle Rogue Valley SNOTEL site for water years 2017–19 compared to median value for water years 1991–2020. [Data from the Natural Resources Conservation Service (2022).]

Because the highway runoff was not measured directly at either the Carter Creek Branch 6 or Wall Creek sites, annual highway-runoff loads were calculated by subtracting the simulated annual loads upstream from the highway from the annual loads downstream from the highway (eq. 2). Annual loads upstream from the highway were simulated using relations between water-quality constituents and specific conductance, as calculated from regional water-quality samples (fig. 7). The annual loads calculated from ODOT deicer application logs can then be directly compared with annual loads of the water-quality constituents downstream to calculate the percentage of each constituent that is reaching the streamgage of interest. Note that the highway of interest for Carter Creek Branch 6 is I–5, not Oregon State Route 273, so the highway input is that from the crossings of I–5 with all branches of Carter Creek upstream from USGS station 14348430.

$$HL_{WQCi} = DL_{WQCi} - UL_{WQCi} \quad (2)$$

where

HL_{WQCi} is the annual load of water-quality constituent i from the highway,

DL_{WQCi} is the annual load of water-quality constituent i downstream from the highway, and

UL_{WQCi} is the annual load of water-quality constituent i upstream from the highway.

The annual loading results in table 29 are listed left to right in order of confidence. Results from Carter Creek Branch 1 are considered the most representative because data were available for (1) upstream and highway-runoff specific conductance and (2) highway runoff at this location. Additionally, water-quality sampling from highway runoff at Carter Creek Branch 1 allowed for relations to be developed between specific conductance and all three water-quality constituents of interest. Conversely, results from Wall Creek are considered least representative and having the most uncertainty because only specific conductance data

Table 28. Deicer application rates within the highway catchments of Carter Creek Branch 1, Carter Creek Branch 6, and Wall Creek in the Siskiyou Pass, southern Oregon, water years 2017–18.

[All values are in pounds avoirdupois. Data source: Jon Lazarus, Oregon Department of Transportation, written commun., 2019. Cl, chloride; $MgCl_2$, magnesium chloride; NaCl, sodium chloride; Mg, magnesium; Na, sodium; NA, not applicable]

Water year	Cl from		Total Cl	Mg from		Total Mg	Na from		Total Na
	$MgCl_2$	NaCl		$MgCl_2$	NaCl		$MgCl_2$	NaCl	
Carter Creek Branch 1									
2017	44,400	129,000	173,400	15,300	NA	15,300	NA	112,000	112,000
2018	51,100	32,100	83,200	17,600	NA	17,600	NA	28,000	28,000
Mean values	47,750	80,550	128,300	16,450	NA	16,450	NA	70,000	70,000
Carter Creek Branch 6									
2017	11,500	32,700	44,200	3,960	NA	3,960	NA	28,500	28,500
2018	14,100	8,500	22,600	4,870	NA	4,870	NA	7,400	7,400
Mean values	12,800	20,600	33,400	4,415	NA	4,415	NA	17,950	17,950
Wall Creek									
2017	27,700	64,100	91,800	9,550	NA	9,550	NA	55,800	55,800
2018	37,000	14,900	51,900	12,700	NA	12,700	NA	13,100	13,100
Mean values	32,350	39,500	71,850	11,125	NA	11,125	NA	34,450	34,450

were available at this location, and all other data were estimated using relations with the Carter Creek watershed or regional inputs.

Results from ODOT deicer application logs show that of the three highway catchments of interest, the most deicer application occurred in the greater Carter Creek watershed (Branch 6), which flows downstream to USGS station 14348430. Carter Creek Branch 1 represents a smaller part of that watershed. About one-quarter of deicer application in the greater Carter Creek watershed (Branch 6) was sourced from the section of I–5 that drains into the smaller tributary. Deicer application loading on the stretch of I–5 that drains into Wall Creek was less than for Carter Creek Branch 6, with 2018 application loading values of chloride, magnesium, and sodium ranging from about one-half to about 70 percent of the values recorded in Carter Creek Branch 6.

Lundmark and Olofsson (2007) used a mathematical model to estimate that approximately 45 percent of deicer applied to roads was transported through splash and spray (airborne deposition) on the ground 0–100 meters from the road (and would likely infiltrate into the ground and not appear as highway runoff). By comparison, of the chloride deicer applied to I–5, an estimated 63–65 percent appears in highway runoff (table 29). The small difference in percentage between the three highway catchments was likely due in part to the magnitude of chloride loading, which accounts for more pounds of constituent than magnesium and sodium combined. With small annual loads, discrete measurement or model errors typically result in large percentage errors. For example, an annual measurement bias of 1,000 pounds of constituent would represent about a 4 percent measurement error in chloride application from highway runoff at Carter Creek Branch 1, but the same 1,000-pound bias would result in about a 21 percent error in magnesium annual loading from the same highway catchment.

The 2018 percentage of deicer loading observed in highway runoff varied much more for magnesium (31 to 69 percent) and sodium (0 to 28 percent). The variation in magnesium was likely due in part to accounting for the smallest load in 2018, which is the opposite effect of large chloride loads as discussed in the previous paragraph. Additionally, because magnesium is applied in liquid form as part of $MgCl_2$, it may be more likely than NaCl to be transported either out of the watershed or to a state that is not readily available for riverine transport (such as soil infiltration). Consequently, $MgCl_2$ may not reach highway runoff or downstream detection points in some instances, whereas in other instances it may be applied during storm events and reach those same detection points in greater concentrations.

Table 29. Annual loading of chloride, magnesium, and sodium for water year 2018 calculated from Oregon Department of Transportation deicer logs and U.S. Geological Survey monitoring stations and estimated mean annual results from Stochastic Empirical Loading and Dilution Model (SELDM) scenarios 11 (Carter Creek Branch 1), 14 (Carter Creek Branch 6), and 15 (Wall Creek) in the Siskiyou Pass, southern Oregon.

[Cl, chloride; Mg, magnesium; Na, sodium; NA, not applicable]

Estimated location and (or) source for water-quality constituent loading	Unit of measure	Carter Creek Branch 1 highway runoff			Carter Creek Branch 6 streamflow			Wall Creek streamflow		
		Cl	Mg	Na	Cl	Mg	Na	Cl	Mg	Na
Deicer application logs	Pound	22,600	4,870	7,400	83,200	17,600	28,000	51,900	12,700	13,100
Highway runoff	Pound	14,300	1,630	1,740	54,300	12,100	7,900	32,650	3,950	0
Percentage of applied	Percent	63	33	24	65	69	28	63	3	0
SELDM highway-runoff mean	Pound	7,300	840	2,300	21,500	2,500	6,600	21,000	2,440	6,400
Downstream	Pound	NA[1]	NA[1]	NA[1]	72,100	14,700	11,800	35,000	5,360	5,350
SELDM streamflow mean	Pound	8,300	2,400	4,600	24,000	6,200	12,200	24,400	7,600	14,300

[1]No downstream measurements occurred at this location (highway runoff only).

Within Carter Creek Branches 1 and 6, the 2018 percentage of sodium deicer loading from highway runoff was relatively consistent (24 to 28 percent). In Wall Creek, about the same amount of sodium was recorded downstream as was estimated to have occurred without highway runoff upstream. This result suggests measurement error at Wall Creek because it would be unlikely that none of the sodium applied along I–5 within the Wall Creek watershed would reach the measurement site downstream. A likely source of this measurement error is upstream streamflow. An overestimation of streamflow would result in an increase in the "natural" loading at the site ("natural" in this case meaning loading without deicer runoff from the highway), which would in turn result in an underestimation of the highway-runoff loading because the highway-runoff loading at this site is calculated as the measured loading minus the natural loading. For reference, if a similar sodium load per acre of pavement were to run off in Wall Creek as in the Carter Creek Branch 1 catchment, the highway loading of sodium from Wall Creek would have been about 1,600 pounds in 2018, which would represent about 12 percent of the estimated sodium applied as NaCl.

SELDM estimates of mean annual concurrent runoff loading from highway runoff and mean annual loading downstream were substantially lower than 2018 loading values calculated from ODOT deicer application logs or recorded at USGS streamgages. This difference was because for this study, SELDM was used to account for concurrent runoff rather than annual loading[4]. SELDM calculates loading in this manner in order to evaluate the influence of highways from storm events rather than tabulate annual loads that are largely sourced from background conditions (streamflow upstream from I–5).

The larger annual loading from 2018 compared to SELDM concurrent runoff at Carter Creek Branch 6 and Wall Creek was largely a result of loading from upstream during periods without concurrent flow (no highway runoff). The differences between loading from the highway site on Carter Creek Branch 1 (USGS station 420425122361700) and SELDM results are less obvious because this site directly measured highway runoff. Several factors may be relevant here:

1. Specific conductance values tend to be highest at USGS station 420425122361700 during periods of low flow (see example in fig. 57). Consequently, some of the highest concentrations of chloride, magnesium, and sodium likely occurred during periods of small highway runoff that did not qualify as precipitation events (events with at least 0.1 inches of precipitation) and would thus not have been categorized as concurrent runoff.

2. USGS station 420425122361700 is located within a "cloverleaf" surrounded by I–5 and its exits and receives runoff and snowmelt from non-pavement surfaces within the cloverleaf, which could add to observed loads. Large amounts of snow, some of which may be compacted by plowing, also can alter runoff pathways, resulting in variable contributing areas to the measurement site compared to temperate conditions when snow is not present.

3. As a statistical model, SELDM is designed to estimate long-term average conditions, not replicate individual years. Annual streamflow and water-quality characteristics often vary considerably. With longer monitoring periods, results could be compared to SELDM outputs in a more meaningful way, and the results used to ascertain which input variables might be improved with further refinement.

[4]Annual loads can be calculated in SELDM if the "Lake Package" is used.

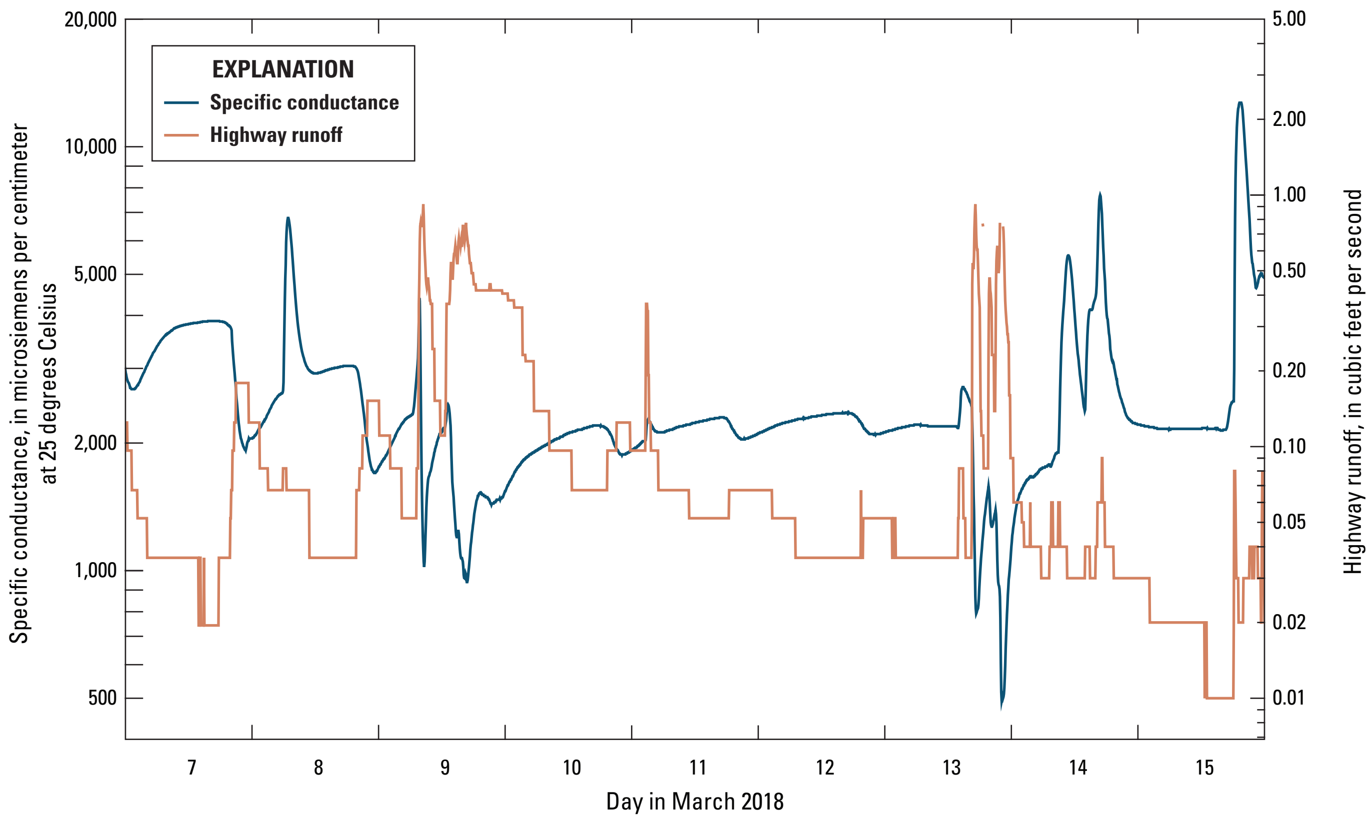


Figure 57. Example of specific conductance and highway-runoff values at U.S. Geological Survey station 420425122361700, Carter Creek Branch 1 in the Siskiyou Pass, southern Oregon, March 7–16, 2018.

Limitations of the Analyses

The analyses described in this report were designed to produce level-1, level-2, and level-3 estimates of stormwater flows, concentrations, and concurrent runoff loads from the Carter and Wall Creek watersheds as well as the road crossings therein to assess relative contributions of applied highway deicer for meeting hypothetical water-quality CMCs. When possible, locally collected data were used. However, when local data were not available, model inputs were estimated using regional data. For example, because no streamflow data were available for the Wall Creek watershed, streamflow input statistics were estimated using neighboring Carter Creek data. For a true level-3 analysis, local data would be used for all inputs.

Additionally, local hydrologic and metrological data were collected for only a 2-year period as part of this study. Therefore, inputs such as streamflow and precipitation variables had a high degree of uncertainty relative to such data from long-term gaging stations. Although long-term, local-data collection prior to a study is likely unrealistic, further studies could provide insight into the level of accuracy of inputs expected using regional data.

Highway-runoff variables were calculated using data collected from USGS station 420425122361700 on Carter Creek Branch 1. For this study, it was assumed that quantities of highway-runoff and water-quality constituent concentrations in the runoff from this site were representative of all sections of I–5. However, highway catchments may have varying rates of runoff conveyance, water or deicer application and accumulation, and vehicular-travel characteristics. Additionally, the drainage area of individual highway catchment areas may not be consistent from storm to storm. Clogged stormwater intakes can route highway runoff into neighboring catchments or away from storm drains and into pervious areas along the highway. The accumulation of snow itself can also impede highway runoff. Areas exposed to more solar input may melt before shaded areas, resulting in asynchronous rates of highway runoff and the potential of highway runoff to flow from one highway catchment to another.

Using the EMC results to evaluate against a hypothetical CMC may add uncertainty to the analysis. Area precipitation events typically last about 10–14 hours (table 6), whereas a CMC is defined for 1 hour. Results in this study were presented in EMCs because (1) SELDM outputs EMC values and (2) there is a paucity of hourly water-quality data from highway runoff, making hourly results less comparable to those of other study areas. Further research would be needed to determine the best approach for evaluating a CMC using EMC results.

Results from the sensitivity analyses are specific to the locations of each simulation and may not apply to other locations. More study would be needed to determine how consistent these sensitivity test results are with what would be observed in other watersheds, especially watersheds that have lower elevations and (or) slopes that are less steep; annual precipitation variables are more consistent along valley floors or other areas with little topographic variation. Also, chloride-deicer application rates are likely to vary considerably in other parts of Oregon. Results should, therefore, be applied carefully to other areas of the State, and each setting should be evaluated thoroughly for differences in hydrological settings and infrastructure conditions.

Summary

The Oregon Department of Transportation (ODOT) relies on the liquid deicer magnesium chloride and solid deicer sodium chloride (NaCl) to keep highways snow free to enable safe and efficient passage for motorists. The use of NaCl is recent for ODOT and was part of a 5-year pilot study designed to evaluate the effectiveness of NaCl for improving roadway conditions and for minimizing adverse environmental impacts resulting from its application on roadways. Preliminary findings from the pilot study suggested that the application of NaCl did not produce observable effects on local vegetation but resulted in elevated levels of chloride in Carter and Wall Creeks in the Siskiyou Pass near the Oregon-California border.

The Stochastic Empirical Loading and Dilution Model (SELDM) estimates combinations of contaminant loads and concentrations from upstream basins and stormwater runoff affecting the water quality of receiving streams. SELDM was used by the U.S. Geological Survey to evaluate highway-runoff, upstream and downstream event mean concentrations (EMCs), exceedance rates of hypothetical criterion mean concentrations (CMCs), and annual concurrent runoff loading from highway runoff and downstream from the intersections with Interstate Route 5 for both Carter and Wall Creeks. (An EMC is a flow-weighted mean concentration for a rainfall-runoff event. A CMC is an estimate of the highest concentration of a water-quality constituent to which an aquatic community can be exposed briefly without resulting in an unacceptable effect. For this study, non-chloride CMCs are hypothetical, and not based on known studies.) Additionally, SELDM was used to evaluate the use of best management practices (BMPs) to mitigate the effects of using chloride deicers. SELDM also was used to evaluate the sensitivity of model results to specific inputs of local data in place of national default data or regional data.

Local and regional data were collected to improve model input estimates. Streamflow data were collected on Carter Creek downstream from the I–5 intersection. Specific conductance data were collected in highway runoff from I–5 into Carter Creek Branch 1, upstream from I–5 on Carter Creek Branch 1, downstream at Carter Creek Branch 6, and downstream from I–5 at Wall Creek. Precipitation data were collected within the Carter Creek watershed. Autosamplers were used to collect water samples from highway runoff within the Carter Creek Branch 1 watershed and also within the watershed and downstream at Carter Creek Branch 6. Water samples were evaluated for specific conductance, chloride, magnesium, and sodium. Additionally, water-quality samples of specific conductance, chloride, magnesium, and sodium were collected from 20 random sites in the greater Bear Creek watershed (in which Carter and Wall Creeks are tributaries) to provide regional (background) inputs for use in the model.

When possible, separate sets of SELDM variables were developed using default national, regional, and local data (level-1, level-2, and level-3 analyses, respectively). SELDM inputs were developed for highway site characteristics, upstream basin characteristics, precipitation statistics, streamflow statistics, volumetric runoff coefficient statistics, and water-quality statistics.

Results showed that downstream EMCs of chloride and magnesium rarely exceeded the hypothetical CMCs established for this study. Conversely, EMCs of sodium routinely exceeded the hypothetical sodium CMC established for this study. Downstream EMCs for all three water-quality constituents were substantially larger than upstream EMCs, indicating that highway runoff is a dominant driver in downstream EMCs. Additionally, mean EMCs were typically much higher than median EMCs, especially for chloride. This shows the highly skewed nature of the EMC populations, with a few relatively high-valued EMCs able to skew mean values to as much as an order of magnitude higher than median values for downstream EMCs, and above two orders of magnitude higher for highway-runoff EMCs.

In general, level-3 analyses tended to produce much less variability in estimated EMCs than level-1 or level-2 analyses. This is because model inputs from level-1 and two analyses are typically from a wider range of conditions than the model inputs developed from the local data acquired for a level-3 analysis.

Eight SELDM scenarios (scenarios 3–10) were developed to evaluate the sensitivity to the presence or absence of local or regional data inputs. In general, local water-quality statistics and streamflow were more influential to estimated EMCs than were other SELDM input statistics. The inclusion of local precipitation data was influential on highway-runoff and downstream mean annual concurrent runoff load SELDM estimates. (Concurrent runoff is the runoff that occurs when there is measurable runoff in both the stream and from the highway, as measured downstream from the highway.) The inclusion of local data had the least influence on exceedance rates of CMCs, but CMCs were most sensitive to the inclusion of local highway-runoff EMC data relative to other model parameters.

The inclusion of a hydrograph extension BMPs resulted in more dilution of highway runoff (a smaller dilution factor) but had no effect on annual concurrent runoff loading of water-quality constituents. The BMP simulations show that a hydrograph extension BMP may result in a slight decrease in peak water-quality constituent concentrations but provide no other benefit to downstream water-quality conditions. Water-quality treatment by structural BMPs (facilities that help to prevent pollutants in stormwater runoff from leaving an area and impacting local waterways) was not simulated because deicing-constituent concentrations are not substantially changed by processes achievable with commonly used BMP designs.

All SELDM results, including sensitivity analyses, are site-specific. For example, at a hypothetical location where regional streamflow data could be used to accurately predict upstream streamflow, the inclusion of local streamflow data would have less influence on model results than was observed in this analysis of Carter Creek. The inclusion of local precipitation data was predicted to improve model output based on the typically high variability of precipitation data at high elevations in mountainous terrain. SELDM results demonstrated that in future studies, preliminary local-data acquisition may be used to ascertain which model inputs are likely to have a high level of variability compared to regional data. In such a manner, the acquisition of local data could be tailored to those inputs most likely to affect results. The identification of which local data to collect can also be informed by the amount of dilution expected. Thus, SELDM can be used to save time and resources that would have otherwise been spent on long-term data collection and analysis.

References Cited

Barnwell, T.O., Jr., and Krenkel, P.A., 1982, Use of water quality models in management decision making: Water Science and Technology, v. 14, nos. 9–11, p. 1095–1107. [Also available at https://doi.org/10.2166/wst.1982.0145.]

Bestland, E.A., 1987, Volcanic stratigraphy of the Oligocene Colestin Formation in the Siskiyou Pass area of southern Oregon: Oregon Geology, Oregon Department of Geology and Mineral Industries, v. 49, no. 7, p. 79–86.

Corsi, S.R., Graczyk, D.J., Geis, S.W., Booth, N.L., and Richards, K.D., 2010a, A fresh look at road salt—Aquatic toxicity and water-quality impacts on local, regional, and national scales: Environmental Science & Technology, v. 44, no. 19, p. 7376–7382. [Also available at https://doi.org/10.1021/es101333u.]

Corsi, S.R., Graczyk, D.J., Geis, S.W., Booth, N.L., and Richards, K.D., 2010b, Supporting information—A fresh look at road salt—Aquatic toxicity and water quality impacts on local, regional, and national scales: Environmental Science & Technology, v. 44, no. 19, p. 7376–7382. [Also available at https://doi.org/10.1021/es101333u.]

Daly, C., Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, no. 2, p. 140–158. [Also available at https://journals.ametsoc.org/view/journals/apme/33/2/1520-0450_1994_033_0140_astmfm_2_0_co_2.xml.]

Federal Highway Administration, 2020, Bridges & Structures—Download NBI ASCII files 2019: Federal Highway Administration web page, accessed October 17, 2020, at https://www.fhwa.dot.gov/bridge/nbi/ascii2019.cfm.

Granato, G.E., 1996, Deicing chemicals as source of constituents of highway runoff: Transportation Research Record, v. 1533, no. 1, p. 50–58. [Also available at https://doi.org/10.1177/0361198196153300108.]

Granato, G.E., 2006, Kendall-Theil Robust Line (KTRLine–version 1.0)—A visual basic program for calculating and graphing robust nonparametric estimates of linear-regression coefficients between two continuous variables: U.S. Geological Survey Techniques and Methods, book 4, chap. A7, 31 p. [Also available at https://pubs.usgs.gov/tm/2006/tm4a7/.]

Granato, G.E., 2008, Computer programs for obtaining and analyzing daily mean streamflow data from the U.S. Geological Survey National Water Information System web site: U.S. Geological Survey Open-File Report 2008–1362, 12 p. [Also available at https://pubs.usgs.gov/of/2008/1362/.]

Granato, G.E., 2009a, Computer programs for obtaining and analyzing daily mean streamflow data from the U.S. Geological Survey National Water Information System web page: U.S. Geological Survey Open-File Report 2008–1362, 123 p. on CD-ROM, 5 appendixes.[Also available at https://pubs.usgs.gov/of/2008/1362/.]

Granato, G.E., 2009b, Surface-water-quality data-miner SWQDM database application (Version 1.0)—Appendix 4 *of* Granato, G.E., Carlson, C.S., and Sniderman, B.S., 2009, Methods for development of planning-level estimates of water quality at unmonitored stream sites in the conterminous United States: Washington D.C., Federal Highway Administration Report FHWA-HEP-09-003, CD-ROM. [Also available at https://www.usgs.gov/software/swqdm-surface-water-quality-data-miner-software-page.]

Granato, G.E., 2010, Methods for development of planning-level estimates of stormflow at unmonitored sites in the conterminous United States: Washington, D.C., U.S. Department of Transportation, Federal Highway Administration Report FHWA-HEP-09-005, 90 p.

Granato, G.E., 2012, Estimating basin lagtime and hydrograph-timing indexes used to characterize stormflows for runoff-quality analysis: U.S. Geological Survey Scientific Investigations Report 2012–5110, 47 p., with digital media, accessed October 17, 2020, at https://pubs.usgs.gov/sir/2012/5110/.

Granato, G.E., 2013, Stochastic empirical loading and dilution model (SELDM) version 1.0.0: U.S. Geological Survey Techniques and Methods, book 4, chap. C3, 112 p., [CD–ROM]. [Also available at https://doi.org/10.3133/tm4C3.]

Granato, G.E., 2014, Statistics for stochastic modeling of volume reduction, hydrograph extension, and water-quality treatment by structural stormwater runoff best management practices (BMPs): U.S. Geological Survey Scientific Investigations Report 2014–5037, 37 p. [Also available at https://doi.org/10.3133/sir20145037.]

Granato, G.E., 2019, Highway-runoff database (HRDB) version 1.1.: U.S. Geological Survey data release, accessed October 17, 2020, at https://doi.org/10.5066/P94VL32J.

Granato, G.E., Carlson, C.S., and Sniderman, B.S., 2009, Methods for development of planning-level stream-water-quality estimates at unmonitored sites in the conterminous United States: Washington, D.C., U.S. Department of Transportation, Federal Highway Administration, Report Number FHWA-HEP-09-003, 53 p.

Granato, G.E., and Cazenas, P.A., 2009, Highway-runoff database (HRDB Version 1.0)—A data warehouse and preprocessor for the stochastic empirical loading and dilution model: Washington, D.C., U.S. Department of Transportation, Federal Highway Administration Report FHWA-HEP-09-004, 57 p.

Granato, G.E., DeSimone, L.A., Barbaro, J.R., and Jeznach, L.C., 2015, Methods for evaluating potential sources of chloride in surface waters and groundwaters of the conterminous United States: U.S. Geological Survey Open-File Report 2015–1080, 89 p. [Also available at https://doi.org/10.3133/ofr20151080.]

Granato, G.E., Desmarais, K.L., Smith, K.P., Weaver, J.C., Glover-Cutter, K.M., Stonewall, A.J., and Fitzgerald, S.A., 2018, Highway-runoff database (Version 1.0.0b): U.S. Geological Survey data release, accessed February 11, 2020, at https://doi.org/10.5066/P9YG44VQ.

Granato, G.E., Ries, K.G., III, and Steeves, P.A., 2017, Compilation of streamflow statistics calculated from daily mean streamflow data collected during water years 1901–2015 for selected U.S. Geological Survey streamgages: U.S. Geological Survey Open-File Report 2017–1108, 17 p. [Also available at https://doi.org/10.3133/ofr20171108.]

Granato, G.E., and Smith, K.P., 1999, Estimating concentrations of road–salt constituents in highway–runoff from measurements of specific conductance: U.S. Geological Survey Water-Resources Investigations Report 99–4077, 22 p. [Also available at https://doi.org/10.3133/wri994077.]

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., and Arnold, J.G., and the R. D. Harmel, and the R. J. Cooper, and the R. M. Slade, and the R. L. Haney, and the J. G. Arnold, 2006, Cumulative uncertainty in measured streamflow and water quality data for small watersheds: Transactions of the ASABE, v. 49, no. 3, p. 689–701. [Also available at https://doi.org/10.13031/2013.20488.]

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p. [Also available at https://pubs.usgs.gov/wsp/wsp2254/.]

Howard, K.W.F., and Haynes, J., 1993, Groundwater contamination due to road de-icing chemicals—Salt balance implications: Geoscience Canada, v. 20, no. 1, p. 1–8.

Kays, M.A., 1970, Western cascades volcanic series, South Umpqua Falls region, Oregon: The Ore Bin, v. 32, no. 5, May 1970, 96 p.

Kelly, V.R., Findlay, S.E.G., Schlesinger, W.H., Chatrchyan, A.M., and Menking, K., 2010, Road salt—Moving toward the solution: Millbrook, New York, The Cary Institute of Ecosystem Studies, 16 p. [Also available at https://www.caryinstitute.org/sites/default/files/public/reprints/report_road_salt_2010.pdf.]

Kunze, A.E., and Sroka, B.N., 2004, Effects of highway deicing chemicals on shallow unconsolidated aquifers in Ohio—Final report: U.S. Geological Survey Scientific Investigations Report 2004–5150, 187 p. [Also available at https://doi.org/10.3133/sir20045150.]

Lundmark, A., and Olofsson, B., 2007, Chloride deposition and distribution in soils along a deiced highway—Assessment using different methods of measurement: Water, Air, and Soil Pollution, v. 182, p. 173–185.

Marsalek, J.H., 1991, Pollutant loads in urban stormwater—Review of methods for planning-level estimates: Journal of the American Water Resources Association, v. 27, no. 2, p. 283–291.

Meranger, J.C., Subramanian, K.S., and Chalifoux, C., 1979, A national survey for cadmium, chromium, copper, lead, zinc, calcium and magnesium in Canadian drinking water supplies: Environmental Science & Technology, v. 13, no. 6, p. 707–711.

National Oceanic and Atmospheric Administration, 2019, National Centers for Environmental Information: National Oceanic and Atmospheric Administration web page, accessed January 24, 2020, at https://www.ncei.noaa.gov/access/search/data-search/global-hourly.

Natural Resources Conservation Service, 2022, Snow water equivalent in Middle Rogue: Natural Resources Conservation Service web page, accessed June 27, 2022, at https://www.nrcs.usda.gov/Internet/WCIS/AWS_PLOTS/siteCharts/POR/WTEQ/OR/Big%20Red%20Mountain.html.

Nilsen, T.H., 1993, Stratigraphy of the Cretaceous Hornbrook Formation, southern Oregon and northern California: U.S. Geological Survey Professional Paper 1521, 89 p.

Oregon Department of Environmental Quality, 2018, Table 30—Aquatic life water quality criteria for toxic pollutants—Aquatic life criteria summary: Oregon Department of Environmental Quality web page, accessed July 26, 2018, at https://www.oregon.gov/deq/FilterRulemakingDocs/tables303140.pdf.

Oregon Spatial Data Library, 2017, Oregon transportation network—2014: Oregon Spatial Data Library web page, accessed October 18, 2017, at https://spatialdata.oregonexplorer.info/geoportal/search;fq=Transportation;q=*roads*.

Rainwater, F.H., 1962, Stream composition of the conterminous United States: U.S. Geological Survey Hydrologic Investigations Atlas HA-61, 3 pls. [Also available at https://doi.org/10.3133/ha61.]

Risley, J.C., and Granato, G.E., 2014, Assessing potential effects of highway runoff on receiving-water quality at selected sites in Oregon with the Stochastic Empirical Loading and Dilution Model (SELDM): U.S. Geological Survey Scientific Investigations Report 2014–5099, 74 p. [Also available at https://doi.org/10.3133/sir20145099.]

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load estimator (LOADEST)—A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods, book 4, chap. A5, 69 p., accessed October 17, 2020, at https://pubs.usgs.gov/tm/2005/tm4A5/.

Salt Institute, 1991, The snowfighter's handbook—A practical guide for snow and ice control: Alexandria, Virginia, Salt Institute Publication SI–1991R, 22 p.

Sauer, V.B., Thomas, W.O., Jr., Stricker, V.A., and Wilson, K.V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Shi, X., Fay, L., Gallaway, C., Volkening, K., Peterson, M.M., Pan, T., Creighton, A., Lawlor, C., Mumma, S., Liu, Y., and Nguyen, T.A., 2009, Evaluation of alternative anti-icing and deicing compounds using sodium chloride and magnesium chloride as baseline deicers—Phase I—Final report: Colorado Department of Transportation, DTD Applied Research and Innovation Branch, Report Number CDOT-2009-1, 270 p.

Smith, K.P., 2017, Loads and yields of deicing compounds and total phosphorus in the Cambridge drinking-water source area, Massachusetts, water years 2009–15: U.S. Geological Survey Scientific Investigations Report 2017–5047, 52 p. [Also available at https://doi.org/10.3133/sir20175047.]

Smith, K.P., and Granato, G.E., 2010, Quality of stormwater runoff discharged from Massachusetts highways, 2005–07: U.S. Geological Survey Scientific Investigations Report 2009–5269, 198 p.

Smith, K.P., Sorenson, J.R., and Granato, G.E., 2018, Characterization of stormwater runoff from bridge decks in eastern Massachusetts, 2014–16: U.S. Geological Survey Scientific Investigations Report 2018–5033, 73 p. [Also available at https://doi.org/10.3133/sir20185033.]

Stonewall, A.J., 2019, Tools for use in Oregon with the Stochastic Empirical Loading Dilution Model: U.S. Geological Survey data release, https://doi.org/10.5066/P9Y6YWG9.

Stonewall, A.J., 2022, Stochastic Empirical Loading and Dilution Model (SELDM) model archive and instructions for the Siskiyou Pass, Oregon: U.S. Geological Survey data release, https://doi.org/10.5066/P9Q1PP61.

Stonewall, A.J., Granato, G.E., and Glover-Cutter, K.M., 2019, 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: U.S. Geological Survey Scientific Investigations Report 2019–5053, 116 p. [Also available at https://doi.org/10.3133/sir20195053.]

Stonewall, A.J., Granato, G.E., and Haluska, T.L., 2018, Assessing roadway contributions to stormwater flows, concentrations and loads by using the StreamStats application: Transportation Research Record, Journal of the Transportation Research Board, 9 p. [Also available at https://doi.org/10.1177/0361198118758679.]

U.S. Environmental Protection Agency, 1992, National pollutant discharge elimination system storm water sampling guidance document: U.S. Environmental Protection Agency Report EPA 883–B–92–001, 177 p.

U.S. Environmental Protection Agency, 2003, Drinking water advisory—Consumer acceptability advice and health effects analysis on sodium: U.S. Environmental Protection Agency Report EPA 822-R-03-006, 29 p., accessed July 24, 2019, at https://www.epa.gov/sites/production/files/2014-09/documents/support_cc1_sodium_dwreport.pdf.

U.S. Environmental Protection Agency, 2019, National pollutant discharge elimination system (NPDES), accessed July 24, 2019, at https://www.epa.gov/npdes.

U.S. Environmental Protection Agency, 2021a, Basic information—NHDPlus (National Hydrography Dataset Plus): U.S. Environmental Protection Agency web page, accessed April 13, 2021, at https://www.epa.gov/waterdata/basic-information.

U.S. Environmental Protection Agency, 2021b, Ecoregions: U.S. Environmental Protection Agency web page, accessed October 17, 2020, at https://www.epa.gov/eco-research/ecoregions.

U.S. Geological Survey, 2018a, StreamStats: U.S. Geological Survey web page, accessed July 26, 2018, at https://streamstats.usgs.gov/ss/.

U.S. Geological Survey, 2018b, Hardness of water: U.S. Geological Survey web page, accessed June 22, 2022, at https://www.usgs.gov/special-topics/water-science-school/science/hardness-water.

U.S. Geological Survey, 2020c, Streamflow measurements for Oregon—USGS 14348430 unnamed trib to wbr Carter Creek, near Ashland, OR: National Water Information System web interface, accessed August 17, 2020, at https://waterdata.usgs.gov/or/nwis/measurements/?site_no=14348430&agency_cd=USGS.

U.S. Geological Survey, 2020a, Streamflow measurements for Oregon—USGS 420425122361700 highway runoff site nr I5 and old hwy 99: U.S. Geological Survey National Water Information System web interface, accessed August 17, 2020, at https://waterdata.usgs.gov/or/nwis/measurements/?site_no=420425122361700&agency_cd=USGS.

U.S. Geological Survey, 2020d, Water quality samples for Oregon—USGS 14348430 unnamed trib to wbr Carter Creek, near Ashland, OR: U.S. Geological Survey National Water Information System web interface, accessed Aug 17, 2020, at https://nwis.waterdata.usgs.gov/or/nwis/qwdata/?site_no=14348430&agency_cd=USGS&inventory_output=0&rdb_inventory_output=file&TZoutput=0&pm_cd_compare=Greater%20than&radio_parm_cds=all_parm_cds&format=html_table&qw_attributes=0&qw_sample_wide=wide&rdb_qw_attributes=0&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=brief_list.

U.S. Geological Survey, 2020b, Water quality samples for Oregon—USGS 420425122361700 highway runoff site nr I5 and old hwy 99: U.S. Geological Survey National Water Information System web interface, accessed Aug 17, 2020, at https://nwis.waterdata.usgs.gov/or/nwis/qwdata/?site_no=420425122361700&agency_cd=USGS&inventory_output=0&rdb_inventory_output=file&TZoutput=0&pm_cd_compare=Greater%20than&radio_parm_cds=all_parm_cds&format=html_table&qw_attributes=0&qw_sample_wide=wide&rdb_qw_attributes=0&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=brief_list.

Wells, F.G., 1956, Geologic map of the Medford quadrangle, Oregon-California: U.S. Geological Survey, GQ 89.

World Health Organization, 2020, Calcium and magnesium in drinking-water—Public health significance: Geneva, Switzerland, World Health Organization, 180 p., accessed April 24, 2020, at https://apps.who.int/iris/bitstream/handle/10665/43836/9789241563550_eng.pdf;sequence=1.

For information about the research in this report, contact
Director, Oregon Water Science Center
U.S. Geological Survey
2130 SW 5th Avenue
Portland, Oregon 97201
https://www.usgs.gov/centers/oregon-water-science-center

Manuscript approved on August 24, 2022

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma Publishing Service Center

Stonewall and others—**Assessing the Impact of Chloride Deicer Application, Siskiyou Pass, Oregon**—SIR 2022–5091

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20225091