ESTIMATING THE RISKS FOR ADVERSE EFFECTS OF TOTAL PHOSPHORUS IN RECEIVING STREAMS WITH THE STOCHASTIC EMPIRICAL LOADING AND DILUTION MODEL (SELDM)

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ABSTRACT
Studies from North Carolina (NC) indicate that increasing concentrations of total phosphorus (TP) and other constituents are correlated to adverse effects on stream ecosystems as evidenced by differences in benthic macroinvertebrate populations in streams across the state. As a result, stringent in-stream criteria based on the Water Quality Assessed by Benthic macroinvertebrate health ratings (WQABI) have been proposed for regulating TP concentrations in stormwater discharges and for selecting stormwater best management practices (BMPs). The WQABI criteria concentrations may not be suitable for evaluating stormwater discharges because they are based on baseflow concentration statistics, the criteria do not include a clearly defined allowable exceedance frequency, and there are substantial uncertainties in estimating the quality of runoff, BMP discharge, and receiving waters for sites without monitoring data. The Stochastic Empirical Loading and Dilution Model (SELDAM), which was developed by the U.S. Geological Survey in cooperation with the Federal Highway Administration, was used to simulate the quality of runoff, BMP discharge, and receiving waters to evaluate risks for water-quality exceedances with different criteria concentrations, allowable exceedance frequencies, and selected water-quality statistics. Water-quality data from two neighboring basins in the Piedmont ecoregion in NC were used to simulate in-stream stormwater quality. Data collected at 15 sites in NC were used to simulate runoff quality. Statistics for stochastic modeling of volume reduction, hydrograph extension, and water-quality treatment by BMPs, were used to simulate potential effect of these treatments on discharge quality and downstream stormwater quality. Results of these long-term 30-year simulations were used to evaluate criteria concentrations, the potential frequency of water-quality exceedances, and the effect of data selection on risks for water-quality exceedances. The simulations indicate that the potential frequency for exceeding instream and stormwater discharge criteria depend on the detailed definition of the criteria and the data that are selected for simulating water quality. Data and simulation results indicate that the baseflow concentrations do not represent stormwater concentrations, even in predominantly forested basins. There is substantial uncertainty in applying stormwater statistics to unmonitored sites, even if these statistics are applied to neighboring basins such as in this example. Over a period of several years (or more) it would be impossible to meet many of the proposed instream and stormwater discharge quality criteria unless these criteria include an allowable exceedance frequency because stormwater concentrations commonly vary by orders of magnitude. Selection of BMPs by using concentration reduction as the sole criteria may underestimate potential benefits of BMPs that also provide volume reduction, which reduces discharge loads, and hydrograph extension, which increases the dilution of runoff into a larger proportion of the upstream stormflow. Results of this study indicate the potential benefits of the multi-decade simulations that SELDM provides because these simulations quantify risks and uncertainties that affect decisions made with available data and statistics. Results of the SELDM simulations indicate that the WQABI criteria concentrations may be too stringent for evaluating the stormwater quality in receiving streams, highway runoff, and BMP discharges; especially with the substantial uncertainties inherent in selecting representative data. INTRODUCTION
Several studies from North Carolina (NC) indicate that increasing concentrations of total phosphorus (TP) are correlated to adverse effects on stream ecosystems as evidenced by differences in benthic macroinvertebrate populations from stream to stream (McNett and others, 2010; Winston and others, 2012). Elevated TP concentrations may be an indicator of general water-quality degradation in receiving streams rather than the primary cause of the observed differences in macroinvertebrate populations. For example, herbicide and pesticide applications associated with fertilizer applications could be an underlying driver for the observed adverse effects (Nowell and others, 2014). The studies that identify TP as a constituent of concern also identify several other constituents that also are correlated to changes in benthic macroinvertebrate populations in NC streams (McNett and others, 2010; Winston and others, 2012) and correlation does not prove causation (Helsel and Hirsch, 2002). It is, however, widely recognized that elevated TP concentrations do contribute to adverse effects on water quality and aquatic
ecosystems in streams, lakes, reservoirs, and estuaries (Litke, 1999; U.S. Environmental Protection Agency, 2000a,b,c; 2000, 2009; Smith and others, 2007; Dubrovsky and others, 2010; McNett and others, 2010; Winston and others 2012). Concerns about potential adverse effects of nutrients in NC are widespread. For example, there are 10 completed total maximum daily load (TMDL) analyses for nutrients or aquatic weeds in receiving waters in NC (North Carolina Department of Environment and Natural Resources, 2015).

Studies done in NC also have proposed that the concentrations of effluent from stormwater control measures, commonly known as best management practices (BMPs), should be based on a stream-quality designation within each ecoregion (McNett and others, 2010; Winston and others 2012). McNett and others (2010) used median in-stream concentration values with macroinvertebrate health ratings to set “target nutrient concentrations” by ecoregion; this approach was named the Water Quality Assessed by Benthic macroinvertebrate health ratings (WQABI) method. McNett and others (2010) indicate that the target concentrations would be set by ecoregion and adjusted for ambient water-quality conditions. However, McNett and others (2010) do not explicitly define the method for calculating their median in-stream value. For example, it could be the median of monitoring station medians, the median of station means, or the median of all concentration data from stream monitoring stations that meet the associated macroinvertebrate criteria. Within the Piedmont ecoregion, McNett and others (2010) established the WQABI target phosphorus concentrations by using the median in-stream values of 0.06 milligrams per liter (mg/L) for streams designated as Excellent, 0.11 mg/L for a Good designation, 0.13 mg/L for a Good-Fair designation, 0.22 mg/L for a Fair designation, and 0.63 mg/L for a Poor designation. If these values represent the medians of sites that meet the biological criteria then the use of the term “target” suggests that a median could exceed the stated concentration value and still meet the biological criteria. In this case it is unclear what concentration defines the threshold between categories. If these concentrations are interpreted as upper thresholds (for example, sites with median concentrations less than 0.06 mg/L meet the Excellent criteria), then the status of sites with median concentrations greater than 0.63 mg/L is undefined. In comparison, the U.S. Environmental Protection Agency (2000a) developed a suggested upper-limit criterion for total phosphorus in rivers and streams of 0.03 mg/L based on the 25th percentile of the median concentrations in the Piedmont ecoregion. In this paper, the concentration values will be interpreted as upper-limit thresholds because this is the common method for specifying water-quality criteria but comparison to the median also are discussed (U.S. Environmental Protection Agency, 1994, 2000a, 2014, 2015).

Water-quality criteria commonly are defined with an allowable exceedance frequency in recognition of large variability in concentrations and flows that may occur over a long period of time (U.S. Environmental Protection Agency, 1994). The U.S. Environmental Protection Agency (1994) selected a once in three year exceedance frequency as a protective measure to provide for ecological recovery from periods of severe stress. If it can be assumed that the target stormwater effluent concentration is also the median then, McNett and others (2010) may be specifying a 50 percent exceedance concentration. McNett and others (2010), however, do not explicitly define an exceedance frequency. If the WQABI target concentrations are applied as an upper limit, which is the standard method for establishing water-quality criteria (U.S. Environmental Protection Agency, 1994, 2014, 2015), then it is conceivable that the standard three-year exceedance frequency also may be applied. Without an allowable exceedance frequency to define the risk of exceedance, the WQABI thresholds can be interpreted as deterministic limits. Use of a deterministic concentration criterion as a quality metric does not account for stochastic variations in stormflows, concentrations, and loads from developed areas, in BMP effluent, and in receiving streams. This is relevant to the application of the WQABI values as concentration-criterion thresholds because the median of receiving-water concentration data that is representative of baseflow quality will not characterize instream concentrations during periods of stormflow, especially for constituents that are associated with sediment transport (Glysson, 1987; North Carolina Department of Environment and Natural Resources, 2010, 2012, Granato and others, 2009; Smith 2013).
The WQABI thresholds also have been used in other studies to evaluate the quality of runoff and the potential effectiveness of BMPs in NC. Winston and others (2012) adopted the WQABI thresholds, as “target” nutrient concentrations, but applied these concentration criteria to median BMP effluent concentrations from the literature. Winston and others (2012) do not discuss an allowable exceedance frequency, but use of the median BMP effluent concentration implies an allowable exceedance frequency of 50 percent. Winston and others (2015) compare bridge-runoff and BMP effluent quality to in-stream water quality standards to assess the need for stormwater treatment. They compare the bridge runoff and BMP effluent concentrations and recommend selection of BMPs based on the percentage of runoff or effluent concentrations, rather than the resulting receiving-water concentrations, that are less than or equal to the WQABI Excellent and Good target concentrations. The WQABI thresholds may be appropriate for comparing potential effectiveness of different BMPs, but the ultimate objective is to develop BMP discharge-concentration criteria based on these ambient receiving-stream quality thresholds (McNett and others, 2010; URS Corporation, 2012).

The effect of runoff on the quality of receiving waters depends on the concentration, flow, and duration of runoff and the concurrent upstream concentration and flow, each of which may vary by orders of magnitude from storm to storm. Therefore, decisionmakers need stochastic information about the quality and quantity of runoff, potential effects on receiving waters, and the potential effectiveness of mitigation measures to assess the risks of adverse effects on the quality of receiving waters (Granato and Jones, 2014). As a result of the implementation of TMDL regulations, scientists, engineers, and decisionmakers have become increasingly aware of the importance of considering random variation in the quantity and quality of highway runoff, urban runoff, and receiving-water stormflows during runoff periods. However, information about long-term frequencies, magnitudes, and durations of runoff concentrations and loads (the products of measured stormflow and concentration) is difficult and expensive to obtain.

A requirement for representative monitoring at any site where development or redevelopment may occur would delay the process and incur substantial costs for stormwater sampling. Furthermore, on-site monitoring will not define the post-development water-quality.

Stochastic modeling methods can be used to estimate potential effects of runoff and the potential effectiveness of mitigation measures (Di Toro, 1984; Schwartz and Naiman, 1999; Granato, 2013a,b; Granato and Jones, 2014). The Stochastic Empirical Loading and Dilution Model (SELDM), which was developed by the U.S. Geological Survey (USGS) in cooperation with the Federal Highway Administration (FHWA), is designed to provide risk-based information from long-term (multi-decade) stochastic simulations that are based on available data and statistics (Granato, 2013a,b). With SELDM, decision makers can estimate risks for water-quality exceedances in the upstream receiving water, in runoff from the site of interest, in BMP effluent, and in the receiving water downstream of the stormwater outfall (Granato, 2013a,b; Granato and Jones, 2014; Risley and Granato, 2014).

The purpose of this paper is to provide a hypothetical case study to compare application of the WQABI BMP-effluent evaluation criteria for TP proposed by McNett and others (2010) to stochastic simulations of upstream, highway runoff, BMP effluent, and downstream concentrations. Data and statistics from two streams in the Piedmont ecoregion are used to evaluate application of these concentration criteria. This stream-quality data, regional water-quality data for the Piedmont ecoregion, and highway-runoff concentrations measured on 15 bridge sites in NC (Wagner and others, 2011) also are used to assess the potential for estimating risks for water-quality exceedances at a site of interest with or without available water-quality data. In this study, statistics are calculated with the logarithms of concentrations because such data commonly fit a lognormal or log-Pearson Type III distribution (Di Toro, 1984; Helsel and Hirsch, 2002; Novotny, 2004; Granato and others, 2009; Granato, 2013b). This hypothetical case study also demonstrates the type of risk-based information that SELDM can provide.
BACKGROUND IN-STREAM CONCENTRATIONS

Background in-stream concentration data are needed to estimate the water-quality conditions of a selected stream reach. Wagner and others (2011) measured event mean concentrations (EMCs) and baseflow concentrations during the period from March 2009 to April 2010 upstream of a highway crossing at USGS monitoring station 0208524088, Mountain Creek near Bahama, NC, in the Piedmont ecoregion. The area around this monitoring site was selected for analysis because monitoring data are available from this site and two nearby USGS stream water-quality monitoring stations (table 1). The stream-quality data from the two nearby stations, which was collected during the 1988–2004 period, were compiled from the USGS National Water Information System to develop planning-level background water-quality statistics by ecoregion (Granato and others, 2009). These stream-quality data may be used to compare the deterministic WQABI criteria designations with variations in measured and simulated data.

Figure 1 is a boxplot that shows different populations of sample values in comparison to the WQABI criteria. The medians of all samples and baseflow samples from USGS stations 0208524090 and 0208650112 are less than the Excellent TP criterion concentration of 0.06 mg/L for the Piedmont ecoregion. In both cases, 95 percent of baseflow samples also are less than the Excellent criterion concentration. The median of instantaneous stormflow samples for station 0208524090 is between the Good and Excellent criterion concentrations and all stormflow concentrations are less than the Poor criterion concentration. The median of instantaneous stormflow samples for station 0208650112 is less than the Excellent criterion concentration and all stormflow concentrations are less than the Fair criterion concentration. These results are to be expected because of the low percentage of development and the high percentage of forest lands in the basin draining to station 0208650112 (table 1). The differences between concentrations measured at station 0208524090 on Mountain Creek and in the neighboring stream basin at station 0208650112 on Flat River trib. also are to be expected because of the larger percentage of cultivated lands in the Mountain Creek watershed. However, when the population of instantaneous stormflow samples measured at 0208524090 is compared with the population of storm EMCs measured at the upstream station 0208524088, the EMC population is substantially and statistically different from the instantaneous concentrations. These differences probably reflect differences in the number of samples and the differences in the period of record rather than differences in the upstream basins because station 0208524090 is 0.6 mi downstream of station 0208524088 and the land-use characteristics are almost identical (table 1). In this area, the upstream EMCs are higher than the instantaneous values and the stream would be classified as exceeding the Fair criterion concentration using the median of the EMC data.

SELDIM simulates flows, EMCs, and loads in a receiving water that are upstream of a BMP outfall or other stormwater input such as highway runoff. SELDM also can simulate the risk that the receiving water may exceed specified concentrations such as the WQABI criteria. The simulated upstream values are concurrent to the simulated highway runoff and BMP discharge durations. SELDM can model upstream concentrations as a random variable, a dependent variable, or as a function of stormflow volume (Granato, 2013a,b). To generate a random population of concentrations, SELDM uses the average, standard deviation, and skew of concentrations or the logarithms of concentrations. To generate a dependent population of concentrations, SELDM uses a regression relation between two constituents with stochastic variations above and below the regression line. To generate a population of concentrations with a transport curve, SELDM uses a regression relation between the simulated stormflow value and the concentration of the constituent of interest with stochastic variations above and below the regression line.
FIGURE 1 Boxplot showing the concentrations of all samples, baseflow samples, within-storm (stormflow), and event mean concentration (EMC) samples. Baseflow and within-storm samples were collected at USGS stations 0208524090 Mountain Creek at Sr1617 near Bahama, NC, 0208524088 Mountain Creek at Sr1616 near Bahama, NC, and 0208650112 Flat River Trib. near Willardville, NC. Stream-quality ratings by McNett and others (2010) are for the Piedmont ecoregion.

TABLE 1 Drainage-basin characteristics of the selected stream monitoring sites and the hypothetical highway-runoff site.

<table>
<thead>
<tr>
<th>USGS Station</th>
<th>Lat Long</th>
<th>DA</th>
<th>Slope</th>
<th>MCL</th>
<th>TIA</th>
<th>Developed</th>
<th>Forested</th>
<th>Cultivated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0208524088 Mountain Creek at Sr1616</td>
<td>36.152 -78.902</td>
<td>7.34</td>
<td>26.3</td>
<td>34,10</td>
<td>1.34</td>
<td>9.01</td>
<td>52</td>
<td>31.9</td>
</tr>
<tr>
<td>0208524090 Mountain Creek at Sr1617</td>
<td>36.1497 -78.8967</td>
<td>8.03</td>
<td>23.9</td>
<td>37,85</td>
<td>1.31</td>
<td>9.29</td>
<td>52.3</td>
<td>32</td>
</tr>
<tr>
<td>0208650112 Flat River Trib.</td>
<td>36.1319 -78.8332</td>
<td>1.14</td>
<td>94.7</td>
<td>11,35</td>
<td>0.11</td>
<td>1.36</td>
<td>92.8</td>
<td>0.308</td>
</tr>
<tr>
<td>Hypothetical highway crossing</td>
<td>36.1319 -78.8332</td>
<td>0.00232</td>
<td>123</td>
<td>660</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

For this case study, the upstream stormflow EMCs were simulated by using 5 alternative sets of input statistics. (1) Upstream TP concentrations statistics calculated with the EMCs measured in Mountain Creek for 8 storms at USGS monitoring station 0208524088 by Wagner and others (2011) are used to simulate upstream concentrations. The average and standard deviation of the base-ten logarithms of EMCs are -0.6913 and 0.1861 for this site. The skew of the logarithms was set to zero because the 95-percent
confidence limit of the coefficient of skew for this sample with 8 storms ranges from about 0.6 to –2.9. Upstream concentrations were calculated (2) with 49 instantaneous stormflow-quality measurements at station 0208524090 on Mountain Creek and (3) with 69 instantaneous stormflow-quality measurements at station 0208650112 on the Flat River tributary. The average, standard deviation, and skew of the base-ten logarithms of stormflow-quality measurements from station 0208524090 are -1.03, 0.347, and 0.27, respectively. The average, standard deviation, and skew of the base-ten logarithms of stormflow-quality measurements from station 0208650112 are -1.51, 0.351, and -0.003, respectively. (4) A two-segment water-quality transport curve calculated by using concentration data from station 0208524090 also was used to simulate upstream concentrations because concentrations of TP varied with streamflow in Mountain Creek (table 2). (5) The planning-level water-quality transport curve developed by Granato and others (2009) by using data from many monitoring stations in the Piedmont ecoregion (table 2) also was used to simulate upstream concentrations of TP for comparison to values generated with site-specific data.

**TABLE 2 Regression-line statistics for transport curves developed by using the logarithms of total phosphorus and streamflow.**

[Transport curves, which are regression equations between streamflow and concentration, were developed by using methods described by Granato and others (2009); total phosphorus concentrations are the logarithms of milligrams per liter and streamflows are the logarithms of cubic feet per second per square mile. MAD median absolute deviation, which is the variability of data above and below the regression line segments.]

<table>
<thead>
<tr>
<th>Transport curve</th>
<th>Segment</th>
<th>Intercept</th>
<th>Slope</th>
<th>MAD</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piedmont ecoregion</td>
<td>1</td>
<td>-1.39794</td>
<td>0</td>
<td>0.30103</td>
<td>-0.686084</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-1.166221</td>
<td>0.337742</td>
<td>0.355447</td>
<td>3.572097</td>
</tr>
<tr>
<td>Station 0208524090</td>
<td>1</td>
<td>-1.522879</td>
<td>0</td>
<td>0.176091</td>
<td>-0.19261</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-1.40992</td>
<td>0.5864632</td>
<td>0.205115</td>
<td>1.764</td>
</tr>
</tbody>
</table>

A 30-year simulation of upstream concentrations, done with the 5 alternative sets of statistics, indicates the risks of exceeding the different WQABI criteria in the receiving waters of these rural basins (figure 2, table 3). Although the median concentrations of all instantaneous samples from each stream would indicate that these streams meet the Excellent WQABI criterion concentration (figure 1), the 30-year simulation results indicate that stormflow concentrations, in the stream upstream of any outfall, frequently exceed the different WQABI criteria-concentration thresholds (table 3). For example, simulated stormflow concentrations in the Flat River Tributary, which is primarily forested, exceed the Excellent, Good, Good-Fair, and Fair criteria concentrations in about 21, 5.4, 3.5, and 0.4 percent of storm events, respectively (figure 2, table 3). Storm-event concentrations simulated by using the various statistics from Mountain Creek also commonly exceed the WQABI criterion concentrations. For example, if the WQABI criteria concentration thresholds compared with simulated stormwater concentrations in Mountain Creek, then the Poor criterion concentration would be exceeded by 0.29 percent of storms modeled by using the EMC statistics, 1.3 percent of storms modeled with the stormflow statistics, and 3.1 percent of storms modeled with the Mountain Creek transport-curve statistics (table 3). The WQABI Poor criterion would be exceeded by about 4 percent of storms modeled by using the Piedmont ecoregion transport-curve statistics.

The URS Corporation (2012) reported biological monitoring results for the Mountain Creek monitoring site (0208524088), which indicate that the stream would receive a Good-Fair rating based on macroinvertebrate population measurements done upstream of the road crossing. The 30-year SELDM simulation results indicates that the associated WQABI Good-Fair criterion concentration (0.13 mg/L) for TP would be exceeded by about 85, 32, and 44 percent of storms if the EMC statistics, random storm statistics, and transport curve statistics from Mountain Creek are used, respectively (figure 2, Table 3). If the transport curve for the Piedmont ecoregion is used to model these stormflows, then about 51 percent of stormflow concentrations would exceed this criterion concentration.
FIGURE 2 Probability plot showing upstream event-mean concentrations simulated by using statistics for event mean concentrations, random stormflow samples, and water-quality transport curves. Stream-quality ratings by McNett and others (2010) are for the Piedmont ecoregion.

Adoption of the WQABI concentrations as official water-quality criteria with the commonly used once in three-year exceedance frequency (U.S. Environmental Protection Agency, 1994, 2014; 2015) would completely change the status of the discharges and receiving streams. The risk for a one-storm exceedance in three years is 0.55 percent based on the long-term average of 58 runoff-producing events per year in this area (Granato, 2010, 2013b). In this case, upstream concentrations in all the simulations with the exception of the Flat-River Tributary random-stormflow statistics and the Mountain Creek event-mean concentration statistics, would fail the WQABI poor criterion (figure 2, Table 3). If the WQABI criteria are established as maximum allowable concentrations without a defined allowable exceedance frequency, the deterministic approach, then none of these upstream stormflow-concentration populations would meet the zero-exceedance criteria. This is despite the fact that most of the median concentrations shown in figure 1 are below the WQABI Excellent or Good criterion concentration. If the allowable exceedance frequency is 50 percent, however, the different simulations would result in an Excellent rating for the Flat River Tributary statistics, a Good, Good-Fair, or Fair rating for the Mountain Creek statistics and a Fair rating for the statistics from the transport curve for the Piedmont ecoregion (figure 2, Table 3).

The simulated EMCs in figure 2 were calculated by using five different sets of statistics to examine the uncertainties involved in estimating constituent concentrations at ungaged sites. These monitoring stations were selected because large data sets were available for both stations. Such data are not available at most stream crossings. The simulated concentrations indicate that the regional transport curve, the Mountain Creek transport curve, and the random storm samples from Mountain Creek produce similar results. In this case, the planning-level ecoregion values may be a good approximation for simulated values that are based on Mountain Creek statistics because the land use values for Mountain Creek (table 1) may be similar to land-use values of the stations used to develop the transport curve for the Piedmont ecoregion. The concentrations simulated by using statistics from the eight EMC samples from Mountain
TABLE 3 Percentage of runoff events that exceed (are greater than) the selected total phosphorus criterion concentrations.

[BMP, stormwater best management practice; mg/L, milligrams per liter; WQABI, Water Quality Assessed by Benthic macroinvertebrate health ratings (McNett and others, 2010)]

<table>
<thead>
<tr>
<th>Water-quality variable</th>
<th>Instream WQABI criteria</th>
<th>NPDES small discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excellent 0.06 mg/L</td>
<td>Good 0.11 mg/L</td>
</tr>
<tr>
<td>Upstream simulations (figure 2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rat River Tributary random stormflows</td>
<td>20.7</td>
<td>5.43</td>
</tr>
<tr>
<td>Mountain Creek event mean concentrations</td>
<td>99.7</td>
<td>91.9</td>
</tr>
<tr>
<td>Mountain Creek random stormflows</td>
<td>70.2</td>
<td>40.4</td>
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<tr>
<td>Mountain Creek transport curve</td>
<td>76.0</td>
<td>50.2</td>
</tr>
<tr>
<td>Pinedale ecoregion transport curve</td>
<td>78.2</td>
<td>57.7</td>
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<tr>
<td>Highway-runoff simulations (figure 3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum of site statistics (Big Ivy Creek bridge 100734)</td>
<td>&gt;99.06</td>
<td>99.9</td>
</tr>
<tr>
<td>Median of NC site statistics</td>
<td>95.8</td>
<td>76.3</td>
</tr>
<tr>
<td>Minimum of site statistics (Little River bridge 310064)</td>
<td>56.9</td>
<td>29.2</td>
</tr>
<tr>
<td>Mountain Creek Bridge 310005</td>
<td>99.3</td>
<td>85.1</td>
</tr>
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<td>BMP-effluent simulations (figure 4)</td>
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<td></td>
</tr>
<tr>
<td>Median of NC site statistics (No BMP)</td>
<td>95.8</td>
<td>76.3</td>
</tr>
<tr>
<td>Swale</td>
<td>99.8</td>
<td>93.6</td>
</tr>
<tr>
<td>Bioretention</td>
<td>79.8</td>
<td>59.0</td>
</tr>
<tr>
<td>Wetland basin</td>
<td>95.1</td>
<td>70.5</td>
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<tr>
<td>Downstream simulations (figure 5)</td>
<td></td>
<td></td>
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<tr>
<td>Rat River Tributary upstream random stormflows</td>
<td>20.7</td>
<td>5.43</td>
</tr>
<tr>
<td>Downstream no BMP</td>
<td>23.9</td>
<td>7.54</td>
</tr>
<tr>
<td>Downstream with swale</td>
<td>21.7</td>
<td>6.97</td>
</tr>
<tr>
<td>Downstream with bioretention</td>
<td>20.4</td>
<td>6.57</td>
</tr>
<tr>
<td>Downstream with wetland basin</td>
<td>21.4</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Creek have a higher median but much less variability than the other simulations based on Mountain Creek and ecoregion statistics. Therefore, a larger percentage of the simulated concentrations based on EMC statistics are greater than the WQABI Excellent, Good, Good-Fair, and Fair concentration criteria, but a smaller percentage of these values are greater than the Poor concentration criterion (table 3). However, the low variability in the simulated EMC-based concentration values may be caused by the small number of EMC measurements in comparison to the large numbers of stormflow measurements from the 20-year sampling effort.

The EMCs simulated by using Flat River Tributary storm-sample statistics are substantially lower than the other simulated concentrations in figure 2. This difference may be attributable to differences in land cover between these adjacent stream basins (Table 1). The Flat River Tributary is about 93 percent forested with less than one percent under cultivation, whereas the Mountain Creek basin is about 52 percent forested with about 32 percent under cultivation. Regional values may provide an initial planning-level estimate, but data selection based on basin properties can be used to refine such estimates. In NC, the U.S. Geological Survey (2015) Streamstats application can be used to obtain basin properties at sites of interest and at data collection sites to facilitate the data-selection process.

**HIGHWAY RUNOFF CONCENTRATIONS**

Selected statistics from a bridge-runoff monitoring project in NC (Wagner and others, 2011) are used in this report as inputs to SELDM, to simulate the populations of TP concentrations in highway runoff. These simulation results are used to assess the potential long-term risks for exceeding the WQABI criterion concentrations and a hypothetical wastewater criterion for small discharges. These simulation results also are used to examine the effect of different highway-data set selections on the potential risks exceeding these criterion concentrations. A recent study indicates that TP concentrations measured in bridge runoff by the USGS are comparable to TP concentrations measured at other highway sites in NC (URS Corporation, 2012). Therefore, these results also may be transferable to non-bridge sites, especially when the variations from bridge site to bridge site are considered (Wagner and others, 2011).

Selecting runoff-quality statistics from monitored sites to represent runoff quality at an unmonitored site is not a well-defined process. Although average daily traffic counts have been reported as a predictive variable, such relations commonly are categorical and the differences among sites may be attributable to the increasing development of surrounding areas that is associated with increasing traffic counts (Driscoll and others, 1990; Smith and Granato, 2010; Wagner and others, 2011; Taylor and others, 2014). Differences in monitoring statistics among sites may not be meaningful without availability of extremely large data sets (for example 25 to 100 events) because of the variability of highway and urban runoff quality (Burton and Pitt, 2002; California Department of Transportation, 2009; Granato, 2013b). Additional uncertainty is introduced by using data from one site to estimate conditions at unmonitored sites.

Four sets of statistics calculated with data collected by Wagner and others (2011) were selected to simulate long-term populations of highway runoff from sites in NC. Data from Bridge 100734 over the Big Ivy Creek near Mars Hill, NC were simulated because EMCs from this bridge were consistently larger than EMCs measured at the other 14 bridge sites. The average, standard deviation, and skew of the base-ten logarithms of EMCs at this site are -0.0994, 0.423, and 0.917, respectively. Data from Bridge 310064 over the Little River near Orange, NC were simulated because EMCs from this bridge were consistently smaller than EMCs measured at the other 14 bridge sites. The average, standard deviation, and skew of the base-ten logarithms of EMCs at this site are -1.11, 0.357, and 1.03, respectively. Data from Bridge 310005 over the Mountain Creek near Bahama, NC were simulated because this site is in the study area. The average, standard deviation, and skew of the base-ten logarithms of EMCs at this site are -0.681, 0.267, and 0.687, respectively. The medians of EMC statistics from all 15 bridge-runoff monitoring sites also were simulated as an approximation that may be used to evaluate potential effects of runoff at unmonitored sites. The medians of the average, standard deviation, and skew of the base-ten logarithms of EMCs are -0.695, 0.357, and 0.687, respectively. The median of these three sample statistics among sites may be a good approximation for simulating runoff-quality populations because
correlations (Pearson’s R and Spearman’s rho) among these statistics are small and correlations to average daily traffic counts also are small; none of the correlations are significant at the 95 percent confidence limits. Lack of significant correlation among statistics indicates that the average, standard deviation, and skew do not covary and therefore using the median of each of these statistics does not misrepresent systematic differences in these statistics from site to site. Lack of significant correlation to average-daily traffic counts among these stations indicates that the statistics may vary randomly from site to site and so the median of the average, standard deviation, and skew of the base-ten logarithms of EMCs may be representative for simulating runoff quality at ungaged sites.

Figure 3 shows results from the selected long-term highway-runoff simulations with probability plots of the monitoring data from all 15 sites monitored by Wagner and others (2011). As the graph indicates, the simulations that are based on the maximum (Big Ivy Creek Bridge 100734) and minimum (Little River Bridge 310064) site statistics do bound most of the measured data and are a good fit to the data measured at the respective sites. The simulated population generated by using the median of statistics from the 15 bridge-runoff monitoring sites is within these bounds and therefore may be a good choice for estimating highway runoff concentrations at unmonitored sites. All four simulated populations are concave up on the probability plot because the logarithm statistics have positive skew values. The positive skew values result in higher concentrations at both ends of the distribution than would be the case for a purely lognormal distribution (with a logarithmic skew of zero). Because the standard deviation of the logarithms of the highway-runoff statistics from Mountain Creek is low in comparison to other sites, the slope of the simulated population on the probability plot is lower than the slope of the other simulated populations. This lower slope results in lower concentrations at the high end and higher concentrations at the low end in comparison to the population simulated with the median-of-site statistics, which has a higher standard deviation. However, the 95-percent confidence interval of the standard deviation of EMCs measured at the Mountain Creek includes the median-of-site statistics so the difference in values between these simulated populations may be because of random variations in samples instead of hydrologic differences among sites. Therefore, the population simulated by using the median-of-site statistics also may be a defensible and conservative surrogate for estimating the risks for exceedances at this site.

If the WQABI criterion concentrations are accepted for regulating discharges to receiving waters then the risk for highway runoff exceedances would indicate the need for a BMP at a given site. Therefore, these WQABI concentration criteria are shown with the simulated highway-runoff EMCs in figure 3 to estimate long-term risks for exceeding these criteria for highway-runoff discharges without BMP treatment. If a determinist approach (no allowable exceedances) or a three-year recurrence frequency (about a 0.55 percent exceedance) is applied then none of the highway-runoff populations would meet any of the WQABI criteria (table 3). If, however, these criteria are applied on the basis of an allowable 50 percent exceedance frequency, then the minimum of site statistics (Little River Bridge 310064) would meet the Good designation, the concentrations from the Mountain Creek Bridge (310005) and the median of site statistics would meet the Fair designation (figure 3, table 3).

An example NPDES permit limit from the Jordan Reservoir TMDL analysis within the Piedmont ecoregion (North Carolina Department of Environment and Natural Resources, 2007) also is shown on figure 3 for comparison to estimated long-term risks for exceeding this criterion concentration. The effective permit concentration is calculated by dividing the permitted annual load by the permitted annual flow. The effective permit concentrations for small point sources, defined as being less than 1 million gallons per day (Mgal/day), range from 0.75 to about 40 mg/L, with a median of 4.1 mg/L in this TMDL. The effective permit concentrations for large point sources range from 0.42 to 1.85 mg/L with a median of 0.91 mg/L in this TMDL. The median criterion for small point sources was used for comparison in this analysis because the volume of runoff from a highway site is very small in comparison to the annual discharge from a large point source. The long-term average annual flow from a lane mile of pavement (12 feet wide by one mile long) calculated by using highway runoff coefficients and the average of precipitation statistics from the Raleigh and Franklinton rain gages (Granato, 2013b) is
0.00343 MGal/day/lane-mile. Based on these statistics about 294 lane-miles of road surface would produce 1 Mgal of runoff per year. If the median concentration of 4.1 mg/L for small point-source discharges was used as the wastewater-discharge criterion concentration, then only the population simulated by using the maximum of site statistics would exceed this three-year (0.55 percent) recurrence frequency; none would exceed a 50 percent recurrence frequency (Figure 3, table 3).

**FIGURE 3** Probability plot showing measured and simulated highway-runoff concentrations based on data collected by Wagner and others (2011). Stream-quality ratings by McNett and others (2010) are for the Piedmont ecoregion. The median effective small-discharge permit limit is the median of the permitted NPDES loads divided by flows for small point sources (less than 1 Mgal/day) as specified in the Jordan Reservoir TMDL (North Carolina Department of Environment and Natural Resources, 2007).

**BMP EFFLUENT CONCENTRATIONS**

The median of site statistics for highway-runoff concentrations described above are used with BMP performance statistics to assess the potential long-term risks for water-quality exceedances for BMP effluents. The BMP performance statistics were calculated by Granato (2014) with data from many sites in the January 2012 version of the international BMP database (www.bmpdatabase.org). The BMP effluent concentrations are simulated by using the BMP-treatment module in SELDM. The SELDM BMP-treatment module has provisions for stochastic modeling of three stormwater treatments: volume reduction, hydrograph extension, and water-quality treatment (Granato, 2013b, 2014). In SELDM, these three treatment variables are modeled by using the trapezoidal distribution and the rank correlation with the associated highway-runoff variable. The SELDM statistics are different from the statistics that are commonly used to characterize or compare BMPs. The SELDM statistical approach is designed to provide a stochastic transfer function to approximate the quantity, duration, and quality of BMP effluent given the associated inflow values for a population of storm events. The SELDM BMP-treatment module also can be used to model the minimum irreducible concentration (MIC), which is the lowest expected effluent concentration from a particular BMP site or a class of BMPs. In these simulations the statistics for concentration reduction and the MIC calculated by Granato (2014) for a bioretention cell, a grassy
swale, and a wetland basin (table 4) are used. The resulting BMP effluent EMCs are compared to the deterministic WQABI criteria proposed by McNett and others (2010) for regulating BMP discharge concentrations and an example NPDES permit limit from the Jordan Reservoir TMDL analysis (North Carolina Department of Environment and Natural Resources, 2007).

TABLE 4 Total phosphorus treatment statistics for the ratios of outflow to inflow concentrations (trapezoidal distribution), the correlation between inflow and outflow concentrations (Spearman’s rho correlation coefficients), and minimum irreducible concentration (MIC) statistics for selected best management practices (BMPs) by category (Granato, 2014).

<table>
<thead>
<tr>
<th>International BMP category</th>
<th>Min</th>
<th>LBMPV</th>
<th>UBMPV</th>
<th>Max</th>
<th>Rho</th>
<th>MIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention</td>
<td>0.013</td>
<td>0.176</td>
<td>0.325</td>
<td>2.339</td>
<td>-0.420</td>
<td>0.010</td>
</tr>
<tr>
<td>Biofilter (grassy swale)</td>
<td>0.105</td>
<td>0.669</td>
<td>0.827</td>
<td>3.556</td>
<td>-0.669</td>
<td>0.010</td>
</tr>
<tr>
<td>Wetland basin</td>
<td>0.056</td>
<td>0.512</td>
<td>0.880</td>
<td>2.158</td>
<td>-0.517</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Figure 4 shows the highway-runoff and BMP effluent EMCs from the 30-year simulations. The BMP effluent EMCs are calculated as a function of the highway runoff discharge concentrations, but because the treatment ratios are stochastic rather than deterministic the percent exceedance of the BMP effluent concentration for any simulated runoff event may not have the same the percent exceedance as the associated highway runoff concentration (Granato, 2013b; 2014). Statistics calculated by using data from the international BMP database indicate that, for TP, BMP effluent EMCs from the bioretention cell, the grassy swale, and wetland basin will exceed inflow EMCs in about 35, 66, and 42 percent of storm events, respectively (Granato, 2014). Both results are to be expected because the pavement runoff is being routed through vegetated areas, which can be a source of TP. It is more difficult to further reduce stormwater concentrations in a BMP if inflow concentrations are low. The negative correlations between inflow concentrations and the stochastic concentration-treatment ratios shown in table 4 indicate that, in general, these BMPs are able to reduce higher concentrations more effectively than lower concentrations. In these simulations, the minimum irreducible concentrations (MICs) shown in table 4 are not achieved in the BMP effluents presented in figure 4. If the simulated minimum instream concentration from the forested Flat River Tributary site (0.002 g/L) is used as an alternative MIC value, then the minimum of the simulated BMP effluent concentrations shown in figure 4 would have been substantially higher than the MIC.

The simulation results in figure 4 show that the selected BMPs do provide some improvements, and can be used to reduce many high concentrations, but cannot be used to reduce all effluent concentrations to a deterministic instream standard. If a deterministic approach (no allowable exceedances) or a once in three-year recurrence frequency (about a 0.55 percent exceedance) is applied, then none of the BMP effluent concentrations will meet any of the WQABI criteria. If these criteria are applied on the basis of an allowable 50 percent exceedance frequency, then the bioretention and wetland-basin effluents would meet the Fair WQABI threshold (figure 4, table 3). These simulations indicate that the grassy swale discharges would meet the Poor WQABI threshold with a 50 percent exceedance frequency. However, discharge quality for all three BMPs would meet the hypothetical effective NPDES limits for small wastewater discharges in the Jordan Reservoir TMDL with a once in three-year recurrence frequency.
FIGURE 4 Probability plot showing simulated highway-runoff and BMP effluent concentrations based on data collected by Wagner and others (2011) and BMP performance statistics calculated by Granato (2014). Stream-quality ratings by McNett and others (2010) are for the Piedmont ecoregion. The median effective small-discharge permit limit is the median of the permitted NPDES loads divided by flows for small point sources (less than 1 Mgal/day) as specified in the Jordan Reservoir TMDL (North Carolina Department of Environment and Natural Resources, 2007).

DOWNSTREAM CONCENTRATIONS
Downstream EMCs during the period of runoff discharge are the sum of concurrent upstream and highway outfall loads divided by the sum of concurrent upstream and highway stormflows (Di Toro, 1984, Schwartz and Naiman, 1999; Granato, 2013a,b; Granato and Jones, 2014). The populations of downstream EMCs indicate risks for potential effects of runoff on receiving waters and the potential effectiveness of BMPs for reducing such risks. In these simulations, site characteristics and random water-quality statistics from the Flat River Tributary near Willardville, NC (USGS Station 0208650112, table 1) were used with site characteristics for a hypothetical four-lane highway crossing (table 1) to evaluate the effect of highway runoff or BMP discharge on downstream EMCs. The Flat River Tributary site was selected because it has a very small drainage area and is almost entirely forested. The drainage area, slope, and main-channel length (along the roadway from one topographic divide to the stream channel), of the hypothetical highway site was based on local topography. The pavement drainage area of the hypothetical highway is about 0.2 percent of the upstream basin and does not include the area of existing roads in the basin; the effect of which are, presumably, already apparent in the upstream water-quality statistics.

Analysis of paired upstream and downstream EMCs provides information about the potential effectiveness of the selected BMPs. About 93.4 percent of downstream stormflow concentrations exceed the paired upstream concentrations in the absence of BMP treatment; thus upstream stormflows are diluted by highway runoff with lower concentrations than the associated upstream EMCs in 6.6 percent of the simulated storm events. In comparison, 77.7, 95.4 or 92.5 percent of downstream EMCs exceed the
associated upstream EMCs if a bioretention cell, grassy swale, or wetland basin is used to treat the highway runoff, respectively. However, relatively few downstream EMCs with BMP treatment exceed the downstream EMCs without BMP treatment even though a substantial percentage of BMP effluent EMCs exceed the associated highway runoff concentrations (about 7.37, 29.5 and 23.2 percent treatment if a bioretention cell, grassy swale, or wetland basin BMP is used, respectively). The differences in instream concentrations with and without the BMPs occur because BMPs also may reduce the load of highway runoff that is discharged to the stream by infiltrating some highway runoff (Granato, 2013b, 2014; Granato and Jones, 2014). These BMPs also extend the time in which the highway site is discharging into the stream (hydrograph extension), which increases the amount of upstream stormflow available for dilution (Granato, 2013b, 2014; Granato and Jones, 2014). Thus, applying the WQABI concentration criteria to evaluate BMP performance, solely based on effluent concentrations, does not account for the relatively large contributions of flow reduction and hydrograph extension for reducing the risks for downstream water-quality exceedances. Nor do the WQABI concentration criteria account for the positive hydrologic benefits that BMP flow reduction and hydrograph extension also provide (Granato, 2014).

Comparison of simulation results indicates that application of WQABI in-stream values to highway runoff or BMP discharges do not change the ecological status in this very small (1.14 square mile) relatively undeveloped (about 93 percent forest) stream basin. If a determinist approach (no allowable exceedances) is applied then the upstream and all downstream EMCs may be classified as Poor by this WQABI standard because some values exceed the 0.22 mg/L Fair concentration standard (figure 5, Table 3). If a standard once in three-year recurrence frequency (about a 0.55 percent exceedance) is applied, then the upstream concentrations would meet the Fair WQABI standard and all the downstream values (with or without the BMP) would exceed the 0.22 mg/L Fair WQABI standard. If these criteria

![Figure 5](image-url)  
**FIGURE 5** Probability plot showing simulated upstream and downstream event-mean concentrations based on data for monitoring station 0208650112 on the Flat River Tributary near Wilardville, North Carolina. Stream-quality ratings by McNett and others (2010) are for the Piedmont ecoregion.
are applied on the basis of an allowable 50 percent exceedance frequency, then the upstream and all the downstream values (with or without the BMP) would meet an Excellent WQABI standard. Therefore, as these simulation results indicate, application of stringent instream criteria to evaluate highway or BMP discharge could lead to decisions to build and maintain BMPs in many locations where they may not make a substantial difference. Given the logistics necessary to build and maintain structural BMPs at every road crossing (Taylor and others, 2014), long-term simulations indicating potential risks for adverse effects in receiving waters may help decisionmakers identify sites where such BMPs may have a positive benefit.

**SUMMARY AND CONCLUSIONS**

Studies from North Carolina (NC) indicate that increasing concentrations of total phosphorus (TP) and other constituents are correlated to adverse effects on stream ecosystems as evidenced by differences in benthic macroinvertebrate populations from stream to stream. As a result, McNett and others (2010) proposed in-stream criteria named the Water Quality Assessed by Benthic macroinvertebrate health ratings (WQABI) to regulate TP concentrations in stormwater discharges. Winston and others (2012) used the WQABI criteria concentrations as a comparison to median BMP concentrations from the literature for selection of a stormwater best management practice (BMP) on the basis of concentration alone. Winston and others (2015) compare bridge-runoff and BMP effluent quality to the WQABI criteria concentrations to assess the need for stormwater treatment. They compare the bridge runoff and BMP effluent concentrations and recommend selection of BMPs based on the percentage of concentrations that are less than or equal to the WQABI Excellent and Good criteria concentrations. Although there are substantial differences in the application of the WQABI criteria concentrations in these papers, the overarching objective is to adjust BMP discharge requirements to ambient water quality. However, questions remain about the application of baseflow water-quality statistics to stormflow quality, application of limits without an allowable exceedance frequency, and the selection of representative water quality for sites without monitoring data.

The Stochastic Empirical Loading and Dilution Model (SELDM) was developed by the U.S. Geological Survey in cooperation with the Federal Highway Administration to facilitate rapid evaluation of stormwater quality that can be used to provide risk-based information from long-term stochastic simulations that are based on available data and statistics. SELDM uses Monte Carlo methods to generate stormflows, event mean concentrations (EMCs), and loads from a site of interest and an upstream basin to provide needed risk-based information. With SELDM, scientists, engineers, and decisionmakers can estimate risks for water-quality exceedances in the upstream receiving water, runoff from the site of interest, BMP effluent, and the receiving water downstream of a stormwater outfall. SELDM also can be used to help resource managers quantify risks and uncertainties that affect decisions made with available data and statistics.

This paper describes a hypothetical case study as an example of the risk-based information about stormflow EMCs that a SELDM analysis can provide for evaluating various water-resource management decisions. These long-term simulations are used to evaluate the potential effects of proposed evaluation criteria and the selection of input statistics on stormwater management decisions. Available water-quality data from two neighboring basins in the Piedmont ecoregion in NC were used to calculate statistics and to do long-term simulations of in-stream quality upstream and downstream of a hypothetical stormwater discharge point. Statistics from runoff-quality data collected at 15 bridge sites in NC were used to do long-term simulations of runoff quality. Statistics for stochastic modeling of three BMP stormwater treatments: volume reduction, hydrograph extension, and water-quality treatment, were used to evaluate the potential effect of these treatments on discharge quality and the downstream stormwater quality. In each case, the potential effects of surrogate data selection methods and long-term risks for water-quality exceedances with different criteria and allowable exceedance frequencies were examined.

Results of the simulations indicate that long-term risks for exceeding instream and stormwater discharge criteria depend on the detailed definition of the criteria and the statistics that are selected for monitored
and unmonitored sites. Baseflow concentration statistics do not represent stormwater concentrations, even in predominantly forested basins in NC. Although median concentrations calculated by using a long record of baseflow and stormflow samples from two neighboring streams would result in an Excellent or Good rating by McNett and others (2010), long-term simulations indicate that stormflow concentrations would frequently exceed these criteria. If the WQABI standards are applied deterministically (no allowable exceedances) then the long-term simulations indicate that all of the simulated populations of upstream, highway runoff, BMP discharge or downstream EMCs would exceed the WQABI Fair criterion (and therefore should be classified as Poor if standard methods for applying water-quality criteria are used), even in these largely forested basins. If a commonly used once in three-year (0.55 percent) water-quality exceedance frequency is applied, then the Flat River Tributary EMCs upstream of the highway would meet the Fair criterion and the downstream EMCs would exceed this criterion with a classification of Poor. If a 50 percent exceedance frequency is used, because the WQABI are based on median streamflow concentrations, then, with the exception of the Mountain Creek event mean concentrations, the populations of upstream EMCs would be classified as Good-Fair or Excellent. Many of the highway and BMP populations would meet the Fair criterion. The upstream EMCs and downstream EMCs, with and without BMPs) would meet the Excellent criterion if the upstream Flat River tributary statistics are used in the simulation.

Both the upstream and highway-runoff simulations indicate that there are substantial uncertainties in the use of available data for estimating conditions at unmonitored sites. The upstream simulations indicate that EMCs calculated by using data from neighboring basins may differ by more than 100 percent, even when these basins have very low impervious fractions and are primarily forested. Similarly simulations made using statistics from several highway-monitoring sites indicate that concentrations can vary by an order of magnitude from site to site.

The WQABI criteria may not be suitable as criteria for evaluating highway-runoff and BMP-discharge quality because data and simulation results indicate that the WQABI baseflow concentrations do not represent stormwater concentrations, even in predominantly forested basins. However, both the highway-runoff and BMP discharge simulations indicate that these stormflow EMCs would not commonly exceed an example criterion concentration, which is based on the median of effective National Pollutant Discharge Elimination System (NPDES) concentrations from small discharge sites.

Simulations of EMCs downstream of a highway-runoff or BMP outfall show that BMP selections made purely on the basis of median effluent statistics may not account for the positive benefits of volume reduction and hydrograph extension. As with the long-term upstream concentrations, the effect of the WQABI rating depends on whether these concentrations are applied deterministically (no exceedances), with a standard once in three-year recurrence interval or as medians of ambient concentrations if they can be exceeded in 50 percent of storm events. Decisions based only on a median or average BMP effluent-concentration criteria do not account for potential benefits of volume reduction and (or) hydrograph extension. Results showing the populations of upstream and downstream concentrations from various simulations indicate that the effect of BMP selection on downstream water-quality is probably well within the uncertainty of input selections. Given the logistics necessary to build and maintain structural BMPs at every road crossing, long-term simulations indicating potential risks for adverse effects in receiving waters may help decisionmakers identify sites where such BMPs may have a positive benefit.

REFERENCES CITED
Granato and Jones


**BIOGRAPHIES**

Gregory Granato is a hydrologist with the USGS New England Science Center. He has been working on highway-runoff issues in cooperation with the Federal Highway Administration for about 20 years. He is author of 7 FHWA reports, 11 USGS reports and 10 other publications related to the quality and quantity of highway runoff. He has a B.S. in Mechanical Engineering from the University of Hartford and a M.S. in Civil Engineering (Environmental) from the University of Virginia.

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