A Case Study Demonstrating Analysis of Stormflows, Concentrations, and Loads of Nutrients in Highway Runoff and Swale Discharge with the Stochastic Empirical Loading and Dilution Model (SELDM)

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Abstract

Decisionmakers need information about the quality and quantity of stormwater runoff, the risk for adverse effects of runoff on receiving waters, and the potential effectiveness of mitigation measures to reduce these risks. The Stochastic Empirical Loading and Dilution Model (SELDM) uses Monte Carlo methods to generate stormflows, concentrations, and loads from a highway site and an upstream basin to provide needed risk-based information. SELDM was designed to help inform water-management decisions for streams and lakes receiving runoff from a highway or other land-use site. The purpose of this paper is to provide a brief description of SELDM and a hypothetical case study demonstrating the type of risk-based information that SELDM can provide. Total nitrogen (TN) and total phosphorus (TP) were selected as example constituents because nutrients are a common concern throughout the Nation and data for receiving waters, highway runoff, and the performance of best management practices (BMPs) are readily available for these constituents.

The case study is hypothetical, but was formulated by using actual data from selected monitoring sites in New England. Data representing streamflow and water-quality were collected at U.S. Geological Survey (USGS) streamgage 01208950 Sasco Brook near Southport, CT, which has a drainage area of 7.38 square miles. In this hypothetical case study a 4-lane highway would replace the current 2-lane road and would have a contributing area of 2.2 acres between the topographic basin divides. Concentrations of TN and TP in highway runoff were simulated with data from USGS highway-runoff monitoring station 423027071291301 along State Route 2 in Littleton Massachusetts. Results of a highway-runoff analysis are shown in relation to three hypothetical discharge criteria for TN and two hypothetical discharge criteria for TP. The risks for exceeding TN discharge criteria of 3, 5, and 8 mg/L for highway runoff are 7.4, 0.83, and 0.13 percent of 1,721 runoff events that may occur during a stochastic 30-year simulation. If a grassy swale is used to treat the runoff, the risks for TN exceedances are reduced to 3.2, 0.33 and 0.03 percent, respectively. The risks for exceeding TP discharge criteria of 0.1 and 0.5 mg/L for highway runoff are 49 and 1.2 percent, respectively. If a grassy swale is used to treat the runoff, the risks for TP exceedances are 57 and 0.8 percent, respectively. The risks for the 0.1 mg/L criterion increase because swales can be a source of TP if pavement concentrations are low. The risks for the 0.5 mg/L criterion decrease because the swale is effective for reducing high TP concentrations. Although the results are mixed for storm-event concentrations, the grassy swale effectively reduces annual loads. Annual loads from the swale are, on average, about 22 percent of highway loads for TN and 62 percent of highway loads of TP because the swale reduces high runoff concentrations and stormflow volumes. Analysis of upstream and downstream concentrations indicates that runoff from the site of interest does not have a substantial effect on instream stormflow concentrations in this example simulation.

Introduction

Decisionmakers need information about the quality and quantity of runoff, potential effects on receiving waters, and the potential effectiveness of mitigation measures to address responsibilities for managing Environmental Impact Statements, National Pollutant Discharge System permits, and efforts to establish Total Maximum Daily Loads (TMDLs). Water-resource managers are concerned about the frequencies, magnitudes, and durations of runoff concentrations and loads (the products of measured stormflow and concentration) to assess the risks of adverse effects on the quality of receiving waters. 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 upstream stormflows for estimating the potential effects of runoff on receiving waters downstream of a runoff discharge point.

In 2013, the U.S. Geological Survey, in cooperation with the Federal Highway Administration, published the Stochastic Empirical Loading and Dilution Model (SELDM) to estimate the risk for stormwater concentrations, flows, and loads to be above user-selected water-quality goals (Granato, 2013a,b). SELDM is designed to be a tool that can be used to transform disparate and complex data into meaningful information about the risk for adverse effects of runoff on receiving waters, the potential need for mitigation measures, and the potential effectiveness of such measures for reducing these risks. SELDM is a mass-balance model; the flows, concentrations, and loads from an upstream basin and a site of interest are added to calculate the flows, concentrations, and loads in the receiving water downstream of a runoff discharge point. SELDM was designed to help inform water-management decisions for streams and lakes receiving runoff from a highway or other land-use site. The highway-runoff and BMP discharge loads simulated by using SELDM can also be used to evaluate contributions from the site of interest to the TMDLs for a basin.

SELDM uses Monte Carlo methods to generate a stochastic population of hundreds to thousands of individual storm-event values for each variable to simulate conditions that may occur over several decades (Granato, 2013a,b; 2014). Unlike deterministic models, SELDM is not calibrated by changing values of input variables to match a historical record. Instead, input variables for SELDM are based on location (latitude and longitude), a few simple site characteristics, and representative statistics for each hydrologic variable. The SELDM development project provided documented statistics from hundreds to thousands of sites to model precipitation, runoff, stormflow, water quality, and BMP performance (Granato, 2013a). The SELDM development project also provided the tools to develop user-defined input statistics from local data rather than published values. SELDM calculates values for 17 primary environmental variables, 15 of which are modeled as stochastic variables; detailed information about these variables is available in the manual. The SELDM BMP-treatment module simulates the volume reduction, hydrograph extension, and concentration reduction for each storm. SELDM can provide planning-level estimates rapidly because it is a database application with an easy-to-use graphical user interface that is preloaded with many of the necessary hydrologic variables.

The purpose of this paper is to provide a brief description of SELDM and a hypothetical case study demonstrating the type of risk-based information that SELDM can provide. This case study will demonstrate stochastic generation of stormflows, concentrations, and loads by using data and statistics available for selected sites in New England. Total nitrogen (TN) and total phosphorus (TP) were selected as the example because nutrients are a common concern throughout the Nation and data for receiving waters, highway runoff, and the performance of BMPs are readily available for these constituents.

Case Study

This case study is for a purely hypothetical situation, but was formulated by using actual monitoring data from selected sites in New England. The upstream basin is defined as the contributing area to USGS streamgage 01208950 Sasco Brook near Southport, CT. The latitude and longitude of the streamgage are 41.15287436 and -73.3059495, respectively. Prestorm streamflow statistics were calculated by using data from the Sasco Brook streamgage. Precipitation statistics were calculated as the average of statistics from two closest precipitation stations (Granato, 2013a,b). Runoff coefficients were calculated by using the impervious fractions of the upstream basin and highway site. The Sasco Brook basin has a drainage area of 7.38 square miles, a main channel length of 27,984 feet (ft), a main channel slope of 53.3 feet per mile (ft/mi), an impervious fraction of 5.5 percent and a basin development factor (BDF) of 0. The BDF is an integer score between 0 and 12 with zero being a completely natural channel and 12 being a fully engineered drainage system (Granato, 2013b). In this hypothetical case study, a 4-
lane highway would replace the current 2-lane road and would have a contributing area of 2.2 acres between the topographic basin divides. This hypothetical highway would have a main channel length of 957 ft, a main channel slope of 191 ft/mi, an impervious fraction of 100 percent, and a BDF of 12.

Highway Runoff Concentrations and Loads

SELDM uses statistics for the quality and quantity of highway-runoff and for BMP-treatment variables to generate a stochastic population of concentrations and loads from the highway and BMP. The SELDM development project (Granato, 2013a) compiled data and statistics for simulating highway runoff and BMP discharge from many sites. Statistics for concentrations of TN and TP in highway runoff were calculated for this case study with data from the USGS highway-runoff monitoring station 423027071291301 along State Route 2 in Littleton Massachusetts (MA) (Smith and Granato, 2010). The average, standard deviation and skew of the common logarithms of event-mean concentrations (EMCs) of TP were equal to -1.05, 0.423, and -0.679, respectively. The arithmetic average and median EMCs were 0.129 and 0.115 milligrams per liter (mg/L) for TP. The average, standard deviation and skew of the common logarithms of EMCs of TN were equal to 0.067, 0.278, and 0.188, respectively. The arithmetic average and median EMCs were 1.42 and 1.09 mg/L for TN. It should be noted that the State Route 2 site has higher nutrient concentrations than about 67 percent of the highway-runoff monitoring sites in the MA dataset (Smith and Granato, 2010). Therefore, concentrations, water-quality exceedances, and loads at other sites in MA and surrounding states may be substantially lower than the values described in this hypothetical example.

BMP performance statistics for dry grass swales, which were calculated by Granato (2014) for use with SELDM will be used for this case study. The statistics for volume reduction, hydrograph extension, concentration reduction, and the minimum irreducible concentration (MIC), which were calculated by using data from the 2012 version of the international BMP database (http://www.bmpdatabase.org/), are shown in table 1. For volume reduction, the correlation to inflow volume is positive indicating that the ratio of outflow to inflow will increase with increasing volume. However, the correlation is not large because many other factors such as antecedent moisture and the duration of the storm also may affect the ratio. For flow extension, the correlation is low for swales because within-swale storage is low in comparison to other BMPs. The correlations between inflow concentrations and the stochastic reduction ratios are strong and negative because it is easier to proportionally reduce large inflow concentrations than to proportionally reduce small inflow concentrations. In these simulations, the selected MIC values were below the BMP discharge concentrations so the selected MIC did not affect BMP performance. The maximum ratios for both TN and TP are greater than one indicating that outflow concentrations may exceed inflow concentrations in some storms.

Table 1. Best management practice (BMP) performance statistics for a dry swale (Granato, 2014b).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>LBMPV</th>
<th>UBMPV</th>
<th>Max</th>
<th>rho</th>
<th>MIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume reduction</td>
<td>0.0602</td>
<td>0.3059</td>
<td>0.4948</td>
<td>1.0845</td>
<td>0.29</td>
<td>NA</td>
</tr>
<tr>
<td>Flow extension</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0.04</td>
<td>NA</td>
</tr>
<tr>
<td>Total nitrogen concentration</td>
<td>0.174</td>
<td>0.642</td>
<td>0.642</td>
<td>2.27</td>
<td>-0.552</td>
<td>0.098</td>
</tr>
<tr>
<td>Total phosphorus concentration</td>
<td>0.105</td>
<td>0.669</td>
<td>0.827</td>
<td>3.556</td>
<td>-0.669</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
Results of the stochastic analysis are shown in relation to three hypothetical discharge criteria for TN and two hypothetical discharge criteria for TP (figure 1). Stochastic simulation with the local precipitation statistics resulted in populations of flows, concentrations and loads from 1,721 runoff-generating events that may occur during a 30-year simulation period. Three hypothetical discharge criteria for TN (3, 5, and 8 mg/L) from the New Hampshire Department of Environmental Services (2010) are used for comparison to the simulated TN concentrations. Two hypothetical criteria for TP (the 0.1 mg/L receiving water criterion and a 0.5 mg/L wastewater-discharge criterion) from Litke (1999) are used for comparison to the simulated TP concentrations. Figure 1 indicates that the risks for exceeding the criteria for TN in highway runoff are 7.4, 0.83, and 0.13 percent of the simulated events, respectively. The risks for exceeding the TN criteria for the associated BMP discharges are 3.2, 0.33 and less than 0.03 percent, respectively. The risks for exceeding the receiving water and wastewater criteria for TP in highway runoff are 49 and 1.2 percent, respectively. The risks for exceeding these TP criteria for the associated BMP discharges are 57 and 0.8 percent, respectively. The grassy-swale performance statistics indicate that this BMP is effective at reducing high concentrations of nutrients, but can contribute nutrients in some storms, especially if inflow concentrations are low (table 1, figure 1). The risks for the 0.1 mg/L criterion increase because the swale can increase low TP concentrations in comparison to pavement runoff. The risks for the 0.5 mg/L criterion decrease because the swale is effective for reducing high TP concentrations. Although outflow concentrations commonly exceed inflow concentrations (about 52 percent of storms for TN and about 34 percent for TP), substantial reductions occur when concentrations are high.

SELDM can be used to calculate loads from a specific site or representative constituent yields (loads per unit area) that can be applied to an entire watershed. With representative water-quality statistics, SELDM can model different road classes or even different land uses. Annual loads from this stochastic 30-year simulation indicate the magnitude and variability of annual loads and the potential reductions from BMP treatment (figure 2). Annual TN yields in highway runoff ranged from 6.99 to 15.7 pounds per acre per year (lb/Ac/yr) with an average of 10.2 lb/Ac/yr (figure 2a). In comparison, the discharge of TN from the grassy swale ranged from 3.21 to 9.71 lb/Ac/yr with an average of 5.04 lb/Ac/yr. TP yields in highway runoff ranged from 0.46 to 1.33 lb/Ac/yr with an average of 0.89 lb/Ac/yr (figure 2b). In comparison, the discharge of TP from the grassy swale ranged from 0.29 to 0.85 lb/Ac/yr with an average of 0.56 lb/Ac/yr. These simulated annual yields could be used with information about the total contributing road area in the basin to help calculate the TMDL for the basin of interest.

In this simulation, variations in loads from year to year are largely attributable to variations in precipitation and flow. Variations in flow account for about 84 percent of the variations in yield from year to year. Annual precipitation from runoff-producing events ranged from 31.2 to 54.4 inches per year with an average of 39.4 inches per year. Highway runoff volumes ranged from 23.1 to 42.4 inches per year with an average of 31 inches per year. In comparison swale discharges ranged from 11.4 to 27.0 inches per year with an average of 17.4 inches. Much of the load reductions evident in figure 2 are from stormflow reductions rather than concentration reductions. The annual-average ratio of outflows to inflows ranged from 0.47 to 0.64 with a 30-year average ratio of 0.56 for the grassy swale BMP. Simulation results from SELDM can be used to help calculate the margin of safety for the TMDL analysis to account for the year-to-year variability in annual loads at a site of interest.
Figure 1. Stochastic populations of total nitrogen and phosphorus concentrations in highway runoff and BMP discharge showing the risks for exceeding hypothetical runoff-quality criteria.
Figure 2. Stochastic populations of total annual nitrogen and phosphorus yields in highway runoff and BMP discharge.
Upstream Concentrations

Upstream flows, concentrations, and loads are modeled for use in the mass-balance calculations to estimate upstream contributions and downstream values (Granato, 2013a,b). SELDM calculates upstream values that are concurrent to the highway-runoff and BMP discharge durations during runoff events. SELDM can model upstream concentrations as a random variable, a dependent variable, or as a function of stormflow volume. 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 constituent of interest and the stormflow with stochastic variations above and below the regression line. If annual estimates of upstream loads are needed for a TMDL analysis the lake-basin analysis in SELDM will calculate a population of annual loads, which includes both runoff and baseflow periods (Granato, 2013b).

Measured concentrations of TN in stormflows in Sasco Brook did not vary as a function of stormflow. Eighty-eight water-quality samples were collected at the Sasco Brook streamgage during the period from October 2007 through September 2014; 46 of these samples were collected during periods of stormflow. EMC measurements are not commonly available for receiving waters so it must be assumed that statistics from a large number of manual samples can approximate the EMC statistics. The TN concentration data collected during runoff events range from 0.46 to 1.9 mg/L with an average of 1.2 mg/L. The average, standard deviation and skew of the common logarithms of the TN concentrations used in this case study were equal to 0.059, 0.136, and -1.1, respectively. Simulated TN concentrations range from 0.15 to 2.0 with an average of 1.2 mg/L. About 98 percent of simulated upstream concentrations exceed the New Hampshire Department of Environmental Services (2010) instream criterion for TN of 0.45 mg/L for coastal tributary streams (figure 3). In comparison, annual average nitrogen concentrations in precipitation from the closest monitoring station (West Point, New York) ranged from 0.23 to 0.73 mg/L with an average of 0.45 mg/L (National Atmospheric Deposition Program, 2014).

Concentrations of TP in Sasco Brook did vary with streamflow so a water-quality transport curve was used to estimate TP EMCs (fig. 4). In this simulation, concentrations of TP in the upstream flow were modeled with a two-segment water-quality transport curve developed using 186 instantaneous values of streamflow and TP concentration measured in Sasco Brook during the 1994-2014 period. The TP concentration data range from less than 0.01 to 0.18 mg/L with an average of 0.037. The data values are not EMCs, but use of a transport curve provides an estimate of the EMC during highway-runoff or BMP discharge periods. Figure 4 shows the measured data, the transport curve, and the simulated upstream concentrations. In theory, the intersection of the segments on the transport curve indicates the transition from baseflow to stormflow. In this case, the first segment has a small negative slope indicating slight dilution with higher base flows. The second segment has a strong positive slope indicating increases in concentration with increasing stormflow. Many of the simulated upstream flow values fall within the baseflow range because the stormflows used are concurrent to the highway runoff, which occurs over a short period of time at the beginning of the upstream stormflow hydrograph. The simulated EMCs range from 0.0044 to 0.24 with an average of 0.35 mg/L; about 1.98 percent of simulated EMCs exceed the receiving water criterion of 0.1 mg/L described by Litke (1999) (figure 3). Sasco Brook is not highly developed and has no wastewater treatment plants so increases in concentration with flow indicate mobilization of TP with runoff and instream flow.
Figure 3. Stochastic populations of total nitrogen and phosphorus concentrations upstream and downstream of the highway showing potential effects of highway runoff and BMP discharges on the receiving stream.
**Downstream Concentrations**

Downstream concentrations are calculated as the sum of loads divided by the sum of stormflows from the upstream basin and the highway runoff or BMP discharge (Granato, 2013b). The populations of downstream concentrations indicate risks for potential effects of runoff on receiving waters and the potential effectiveness of BMPs for reducing such risks (figure 3). Downstream concentrations of TN vary from 0.16 to 2.81 with an average of 1.2 mg/L without the BMP; 98.5 percent of these simulated downstream concentrations exceed the hypothetical 0.45 mg/L receiving-water criterion. In comparison, downstream concentrations of TN vary from 0.16 to 2.01 with an average of 1.19 mg/L with the BMP; 98.3 percent of these simulated downstream concentrations exceed the hypothetical 0.45 mg/L receiving-water criterion. On average, TN concentrations in highway runoff and BMP discharge were about 1.3 and 1.2 times the upstream concentrations, respectively.

Downstream concentrations of TP vary from 0.004 to 0.24 with an average of 0.036 mg/L without the BMP; 1.98 percent of these simulated downstream concentrations exceed the hypothetical 0.1 mg/L receiving-water criterion. Downstream concentrations of TP with the BMP in place and the percentage of excursions with the BMP are within the rounding error of the downstream concentrations without the BMP (figure 3). On average, TP concentrations in highway runoff and BMP discharge were
about 5.1 and 5.4 times the upstream concentrations. The highway contributing area is small in comparison to the upstream basin, even though the drainage area at the streamgage is only 7.38 square miles. The comparatively high TP concentrations in highway runoff are diluted by upstream flow such that the effect on downstream concentrations is negligible, even in this small drainage basin.

Conclusions

SELDM uses Monte Carlo methods to generate populations of flows, concentrations, and loads from a highway site and an upstream basin to provide risk-based information for decision makers to evaluate the effects of runoff on receiving waters. SELDM also uses Monte Carlo methods to model the effects of BMPs on runoff and receiving waters. SELDM is, nominally, a highway runoff model but can be used for different land uses as well. This paper provides a case study based on a stochastic 30-year simulation as an example of the risk-based information that a SELDM analysis can provide. Results of the case study indicate that concentrations in highway runoff and BMP discharges exceed selected wastewater criteria in fewer than 8 percent of runoff events for TN and fewer than 2 percent of runoff events for TP. The analysis of annual runoff yields, which may be useful for TMDL analyses, indicates that addition of the grassy swale BMP can reduce annual loads by about 50 percent. Simulation results indicate that concentrations of highway runoff and BMP discharge from the site of interest are about 1.2 times the upstream concentration of TN and about 5 times the upstream concentration of TP. Although the discharge concentrations are substantially higher than upstream concentrations, runoff from the site of interest does not have a substantial effect on stormflow concentrations downstream of the discharge point in this small (7.38 square mile) basin. Addition of the grassy swale BMP substantially reduces annual loads from the site of interest. Annual loads from the swale are, on average, about 22 percent of highway-runoff loads for TN and 62 percent of highway-runoff loads of TP. However, addition of the swale does not have a substantial effect on instream concentrations because the hypothetical highway contributing area is small in comparison to the upstream basin area at the streamgage.

References

National Atmospheric Deposition Program, 2014, NADP maps and data: accessed on line on November 15, 2014 at http://nadp.sws.uiuc.edu/data/