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Abstract: Ecological studies indicate that impervious cover (IC) greater than approximately 5%–20% may have adverse effects on receiving-stream ecology. It is difficult to separate the effects of runoff quality from other effects of urbanization on receiving streams. This study presents the results of a numerical experiment to assess the effects of increasing IC on water quality using the Stochastic Empirical Loading and Dilution Model (SELDM). Hydrologic and physiographic variables representative of southern New England were used to simulate receiving water quality in a basin with IC ranging from 0.1% to 30%. Simulation results mirror the results of ecological studies; event mean concentrations (EMCs) of total phosphorus (TP) increase proportionally to the logarithms of imperviousness for a given risk percentile. Simulation results indicated that commonly used stormwater treatment methods may be insufficient for mitigating the effects of imperviousness. Therefore, disconnection, rather than treatment, may be needed to protect water quality, and efforts to preserve undeveloped stream basins may be more effective than efforts to remediate conditions in highly developed basins. Results also indicate that commonly used water-quality criteria may be too restrictive for stormwater because TP EMCs frequently exceed these criteria, even in minimally developed basins. **DOI: 10.1061/(ASCE)EE.1943-7870.0001763.**

Introduction

Stormwater runoff from impervious areas has long been a widely recognized contributor to ecological degradation in receiving streams (Paul and Meyer 2001; Shuster et al. 2005; Walsh et al. 2005; National Research Council 2009; Schueler et al. 2009; Baruch et al. 2018; Blaszczak et al. 2019). Stormflows from impervious areas commonly carry a complex variety of constituents, including sediment, nutrients, major ions, metals, herbicides, pesticides, and natural and anthropogenic organic chemicals (Göbel et al. 2007; National Research Council 2009; Zgheib et al. 2012). Nutrients, particularly total phosphorus (TP), in runoff are well-recognized and commonly measured sources of receiving-water degradation (Hobbie et al. 2017; Kaushal and Belt 2012; National Research Council 2009; Yang and Lusk 2018). Phosphorus is the primary limiting nutrient in most freshwater bodies, and most eutrophication management strategies focus on the control of phosphorus inputs (Smith et al. 1999). Despite management efforts to control phosphorus loading, TP concentrations in urban streams and lakes throughout the US have increased by approximately twofold from 2000 to 2014 (Stoddard et al. 2016).

Obtaining meaningful and representative stormwater runoff data to address ecological degradation is difficult and resource intensive. Therefore, measures of impervious cover (IC), which include features such as roads, buildings, parking lots, driveways, and sidewalks, have been used as a surrogate for the effects of runoff on receiving waters (Arnold and Gibbons 1996; ENSR Corporation 2005; National Research Council 2009; Paul and Meyer 2001; Schueler et al. 2009; Shuster et al. 2005). Impervious cover thresholds at which biological, chemical, and physical components of a stream degrade commonly are cited as 5%–20% total IC, although recent studies describe a continuum of negative ecological impacts with increasing imperviousness recognizing the varying levels of water quality in local streams (Arnold and Gibbons 1996; Brabec 2009; Paul and Meyer 2001; Schueler et al. 2009). In New England, the USEPA has implemented a total maximum daily load (TMDL) method that uses the percentage of IC in small-stream basins with biological impairments as a surrogate for individual TMDLs for many different stormwater constituents (ENSR 2005). The USEPA-recommended IC target is generally 9% of total impervious area, and this target can be met by decreasing total impervious area or decreasing directly connected impervious area using structural best management practices (BMPs) (ENSR 2005). Although the EPA IC method is designed to reduce the problem at the source and the action threshold is based on literature values, the IC method is not clearly linked to potential changes in stormwater quality, and the potential for reducing ecological degradation is presumptive rather than quantitative.

Purpose and Scope

The objective of this study was to simulate TP event mean concentrations (EMCs) from developed impervious areas and undeveloped areas in concurrent downstream stormflows over a range of impervious percentages to examine relations between the percentage of IC and the risk for exceeding commonly used water-quality criteria. These relations may provide planning-level estimates of phosphorus EMCs as an explanatory variable for ecosystem changes commonly observed as IC increases in developing drainage basins. Although many water-quality constituents in runoff from impervious areas have adverse effects on receiving waters (Walsh et al. 2005; Brown et al. 2009; National Research Council 2009), TP was

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selected because data are available for runoff, receiving waters, and BMP performance.

Stormwater runoff in a hypothetical stream basin that represents hydrologic and physiographic basin properties in southern New England was simulated using the Stochastic Empirical Loading and Dilution Model (SELDM) to conduct a numerical experiment designed to explore relations between IC and receiving-water quality. These simulations included a range of IC from 0.1% to 30%. A numerical experiment was needed because long-term characterization data for runoff quality, BMP treatment, and background stormwater quality in hydrologically similar basins with varying impervious fractions were not available. The potential effectiveness of structural stormwater control BMPs for decreasing instream concentrations by hydrograph extension, flow reduction, and water-quality treatment were simulated with statistics that are representative of actual BMP performance (Granato 2014). Simulations were done using input values that are representative of southeastern New England because this area is highly developed and is within the area where IC-based TMDLs are being used.

Methods

SELDM is a stochastic runoff-quality model developed by the USGS in cooperation with the Federal Highway Administration to simulate the risks for adverse effects of runoff on receiving waters and provide meaningful information about the potential effectiveness of management measures to reduce those risks (Granato 2013, 2014; Jeznach and Granato 2020). SELDM is nominally a highway-runoff model, but it is a lumped-parameter model that can be used to simulate runoff from almost any land use by using representative basin properties and water-quality statistics. Because SELDM is a lumped-parameter model, the entire IC area was simulated as a single discharge at the point of interest. The IC area was simulated as the "highway site" discharging to the point of interest. The entire pervious area was simulated as the "upstream basin" discharging to the point of interest. The model simulates prestorm flows, precipitation, runoff coefficients, and hydrograph timing variables stochastically using literature and public database-derived statistics from hundreds to thousands of sites (Granato 2013). Unlike deterministic models, which are calibrated by history matching to the outputs, SELDM is calibrated using representative site statistics.

Simulated Hydrology

SELDM simulates stormflows from runoff-generating events using statistics for prestorm streamflows, precipitation, and runoff coefficients (Granato 2013). Individual prestorm streamflows, precipitation event characteristics, and runoff coefficient values are simulated by using the log-Pearson Type III distribution, the two-parameter exponential distribution, and the Pearson Type III distribution, respectively. Furthermore, the effects of antecedent conditions on runoff coefficients are simulated by incorporating the rank correlation to prestorm streamflow. The SELDM user can select regional statistics, statistics from sites that represent a site of interest or user-defined statistics. Statistics available within SELDM for USEPA Level III Ecoregion 59, the Northeastern Coastal Zone, were selected to develop planning-level estimates of prestorm streamflows and precipitation in this study because values for this ecoregion are representative of hydrologic conditions in southeastern New England. The average of streamflow statistics from 79 stream gauges and 31 precipitation stations in the ecoregion were used in the simulations. The proportion of zero prestorm streamflows was 0.00057. The retransformed average, standard deviation, and skew of the logarithms of normalized streamflow (in liters per second per square kilometer) were 11.36, 3.0004, and −0.1358, respectively. The average precipitation volume, duration, and time between storm-event midpoints were 17.8 mm, 9.69 h, and 155 h, respectively. The average, standard deviation, and skew of runoff coefficients for the pervious area were 0.129, 0.099, and 1.08, respectively. The average, standard deviation, and skew of runoff coefficients for the impervious area were 0.769, 0.114, and −0.51, respectively.

Basin Properties

SELDM uses five basin-property variables to simulate the volume and timing of runoff from a site of interest and the upstream basin (Granato 2013). These variables include the drainage area, main channel length, main channel slope, and imperviousness (Granato 2012, 2013). The drainage area, the percentage IC, and the precipitation volumes determine the runoff volumes from each drainage area. A total drainage area of approximately 26 km^2 (10 mi^2) was used for all the simulations because this is a moderately sized basin for Ecoregion 59. The impervious area was increased and the pervious area was decreased proportionally to simulate impervious percentages of 0.1% (to simulate essentially natural conditions) 1%, 2.5%, 5%, 10%, 15%, 20%, and 30% to simulate various levels of development. The timing of runoff from the impervious and pervious areas is determined by the basin lag time, which is simulated using the main channel length, main channel slope, and imperviousness (Granato 2013). Increasing main channel length will increase basin lag time; increasing main channel slope or imperviousness will decrease basin lag time (Granato 2012).

Although the pervious and impervious areas were varied for the different simulations, the sum of areas remained at 26 km^2 and the "upstream" length and slope were held constant, as would be the case for a developing basin. The main channel length and slope of the pervious area were estimated using available physiographic information for stream gauges in the northeastern United States (Granato 2012). The main channel length had a strong correlation to drainage area, with a Spearman's rho value of 0.958; a length value of approximately 10.17 km was calculated as the median channel length for 26-km^2 basins in this area. The main channel slope had a moderately strong correlation to drainage area, with a Spearman's rho value of −0.75; a slope value of approximately 6.17 m/km was calculated as the median channel slope for 26-km^2 basins in this area. These values resulted in a basin lag time of approximately 4 h for the upstream pervious area. Runoff from the pervious area was simulated using a triangular hydrograph with standard stochastic hydrograph-recession ratio statistics (Granato 2012, 2013).

Although the entire impervious area is simulated as a single discharge at the point of interest, the average main-channel length and slope were simulated to represent the timing of runoff from many small impervious areas distributed along the tributaries of the stream above the site of interest. The length of overland flow for contributing areas commonly has been estimated as half the length between stream channels (Carlston 1963). Using this assumption, the flow length has been estimated as half of the reciprocal of drainage density. Bent et al. (2014) calculated drainage density values for 197 streamflow measurement sites in southern New England. In this data set, the drainage areas ranged from 0.728 to 761 km^2 and the drainage density ranged from 0.347 to 2.35 $\mathrm{km/km}^2$. Analysis of these data indicate that, with a rank correlation coefficient (Spearman's rho) of only 0.129, drainage density is not a function of drainage area at these sites in southern New England. The average drainage density for these sites is 1.26 $\mathrm{km/km}^2$, and the reciprocal is approximately 0.8 km. Therefore, the Horton half-distance

Table 1. Event-mean concentration statistics in mg/L for total phosphorus concentrations in urban runoff from 95 sites in September 2016 version of International Stormwater BMP Database

Runoff-quality constituent	Fraction of censored values	Arithmetic statistics			Geometric mean	Logarithmic (base 10) statistics		
		Average	SD	Skew		Average	SD	Skew
Minimum	0.00	0.032	0.015	−0.087	0.029	−1.5315	0.1469	−2.6809
10th percentile	0.00	0.076	0.057	0.383	0.055	−1.2571	0.1918	−1.0322
25th percentile	0.00	0.126	0.088	0.945	0.095	−1.0208	0.2402	−0.2824
Median	0.00	0.223	0.173	1.52	0.159	−0.7988	0.2953	0.3296
75th percentile	0.00	0.418	0.302	2.69	0.279	−0.5541	0.3601	0.7436
90th percentile	0.10	0.739	0.582	3.95	0.435	−0.3616	0.5069	1.3157
Maximum	0.50	3.55	7.27	5.52	3.09	0.4898	0.7771	3.3337

Note: Statistics ranked independently; SD = standard deviation; skew = coefficient of skewness, dimensionless. The runoff-quality statistics are from the September 2016 version of the International Stormwater BMP database.

would be approximately 402 m (Horton 1945). Assuming that the storm sewers are designed to maintain a flow velocity greater than approximately 0.76 m/s to avoid deposition of sand and sediment, an average drainage-system slope of approximately 1.9 m/km is assumed (Peavy et al. 1985). Using these basin properties for the IC areas results in a basin lag time of approximately 6.5 min (Granato 2012). Although the actual flow distance from different impervious areas may range from several meters to a kilometer, the differences in the estimated basin lag times for these distances vary by orders of a few minutes for completely impervious areas (Granato 2012); these differences are small in comparison to the average storm duration (approximately 10 h) in the Northeastern Coastal Zone ecoregion. Runoff from the impervious area was simulated using a hydrograph with an equal rising and falling limb.

Simulated Developed-Area Runoff Quality

The quality of runoff from the developed areas was simulated using EMC data for unfiltered TP from the September 2016 version of the International Stormwater BMP Database. EMC data collected from BMP inflow-monitoring points represent stormwater from developed areas that is routed to the BMPs for treatment. Queries were written to identify BMP-inflow monitoring sites, obtain stormwater-quality data, and calculate sample statistics for each monitoring site to represent urban-runoff quality for nonhighway land uses. A simple replacement method was used to estimate statistics for sites with one or more values below the reported detection limits (censored data). The International Stormwater BMP Database does not provide the means to calculate censored values using statistical methods but instead has a concentration field that has either an uncensored value or half the reported detection limit. Antweiler and Taylor (2008) indicated that substituting concentrations equal to half the detection limits was sufficient for developing planning-level estimates for water-quality statistics. Croghan and Egeghy (2003) demonstrated that substituting concentrations equal to the detection-limit concentration divided by the square root of 2 produced unbiased estimates up to censoring levels of approximately 50%. Therefore, the Croghan and Egeghy (2003) approach was used and only data sets with censoring levels that were less than or equal to 50% of concentrations were included for estimating sample statistics. Approximately 18% of the TP data sets obtained from the International Stormwater BMP Database have one or more censored values.

SELDM uses the average, standard deviation, and skew of the logarithms of EMCs to simulate a population of runoff concentrations from the developed area. There are wide ranges in the site statistics for TP in the International Stormwater BMP Database (Table 1, Fig 1). For example, the maximum geometric mean is 107 times the minimum geometric mean for TP. EMC statistics were grouped by land-use categories, but there are no clear relations between land-use category and the magnitude of the geometric means (Fig. 1). The statistics listed in Table 1 were ranked and selected independently; the averages, standard deviations, and skew values on each row in the table may be from different study sites. To evaluate the validity of this approach, a rank-correlation analysis was done to assess potential relations among the average, standard deviation, and skew of the logarithms of EMC values. The rank correlation coefficient between the average and standard deviation and the average and skew of the logarithms of TP EMCs were approximately −0.17 and −0.18, respectively. The rank correlation coefficient between the standard deviation and skew of the logarithms of TP concentrations was approximately 0.1. Analysis of the site statistics indicated that the average, standard deviation, and skew of these EMC data are not correlated. Therefore, the developed-area runoff quality was simulated using the median of the average (−0.7988) and standard deviation (0.2953) of the logarithms of concentrations (Table 1).

Only 24% of logarithmic skew values were outside the 95% confidence limits of a zero skew for TP and the statistically significant skew values had both positive and negative signs, so the developed-area runoff quality was simulated as a lognormal variable with a skew of zero. Use of zero skew also may be warranted because the logarithmic skew values were only weakly correlated with the average and standard deviation of the logarithms of EMCs. This approach also is supported by the literature because the lognormal distribution commonly is used to characterize and simulate urban-runoff quality (Di Toro 1984; Novotny 2004; National Research Council 2009).

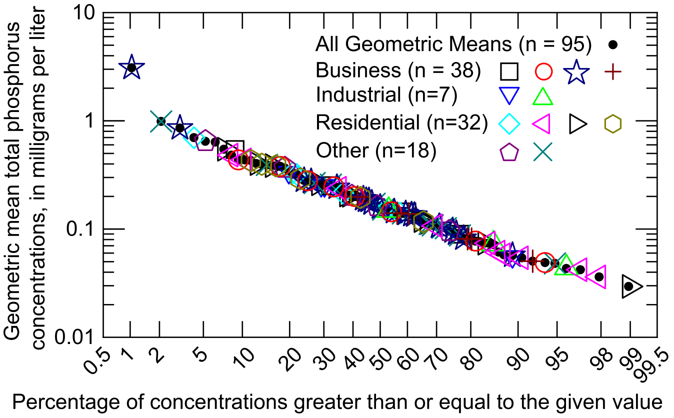

Fig. 1. Probability plot showing distribution of geometric means of TP EMCs and land-use categories from International Stormwater BMP Database.

Simulated Upstream Water Quality

The upstream water quality was simulated using a water-quality transport curve with stochastic variations above and below the regression line. A water-quality transport curve is a regression relation between streamflow volumes and constituent concentrations (O'Connor 1976; Glysson 1987; Granato 2006, 2013). A two-segment water-quality transport curve (Fig. 2) was developed using the logarithms of paired streamflow and concentration data with the Kendall Theil Robust Line program (Granato 2006). The transport curve was developed with 159 paired streamflow and TP concentration values measured at USGS Station 01170100 Green River near Colrain, Massachusetts, during the period from March 25, 1993, through August 2, 2016. These data are available in the USGS National Water Information System database (USGS 2019). Data from this stream gauge were selected because the basin is rural (approximately 91% forest and 0.28% impervious based on the USGS StreamStats delineation), and paired values of streamflow and concentration were available over a large range of flows. Among these paired measurements, streamflow ranged from 2.657 to 1,431 $\mathrm{L/s/km^2}$ and TP concentrations ranged from 0.002 to 0.125 mg/L. The equation for the first segment is

$$\text{Concentration} = 0.004 \times MAD^{K_{random}} \tag{1}$$

and is used when streamflow is less than 73.851 $\mathrm{L/s/km^2}$ and the equation for the second segment is

$$\text{Concentration} = 0.00038 \times \text{Streamflow}^{0.54738} \times MAD^{K_{random}} \tag{2}$$

and is used otherwise. In these equations MAD is the median absolute deviation of the regression residuals (1.33 for the first segment and 1.61 for the second segment) and K_{random} is the random normal variate, which is used to simulate the scatter of concentrations above and below the regression line. MAD is used to simulate variability rather than the standard deviation of residuals because the transport curve is being used to simulate EMCs rather than instantaneous concentrations (Granato 2013). The transport curve is being used as a planning-level estimate of the central tendency of EMCs for a given streamflow value. The zero slope of the first segment indicates that concentration varies randomly with a lognormal distribution with a geometric mean of 0.004 mg/L when streamflow is below 73.851 $\mathrm{L/s/km^2}$. Concentration varies stochastically with flow and lognormal random variation above this threshold. Although the maximum flow measured concurrently with TP sampling is approximately 1,431 $\mathrm{L/s/km^2}$, the regression equation produces TP concentrations that are well within observed TP concentrations in minimally developed basins in southern New England when much higher flow rates are simulated.

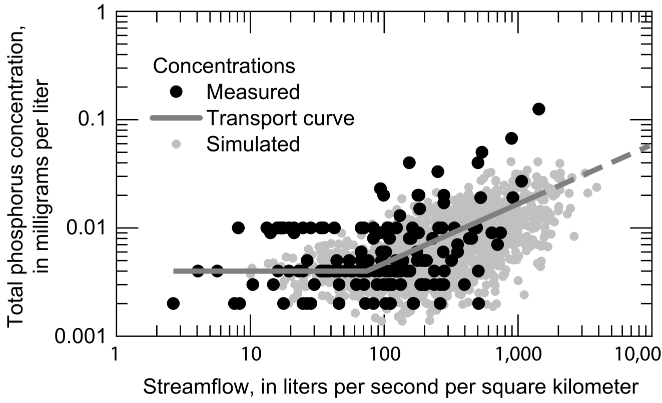

Fig. 2. Best-fit two-segment water-quality transport curve developed with data from Green River near Colrain, Massachusetts, and concentrations simulated using transport curve with random variability.

Simulated Runoff Treatment

SELDM can simulate three stormwater-treatment mechanisms, including runoff hydrograph extension, volume reduction, and water-quality treatment, using a trapezoidal distribution with correlation to the inflow values (Granato 2013, 2014; Granato and Jones 2014). Three types of generic BMPs were simulated: one with hydrograph extension only, one with flow reduction only, and one comprehensive BMP with hydrograph extension, flow reduction, and water-quality treatment. BMPs with hydrograph extension lengthen the runoff-discharge hydrograph, increasing the amount of concurrent upstream stormflow by retention, thereby increasing the dilution of runoff into a greater volume of receiving-water stormflow. Hydrograph extension may reduce the instantaneous erosivity of stormflow but may increase the fully mixed mass-balance concentration at the mixing point if upstream concentrations exceed the runoff concentrations. BMPs with volume reduction decrease stormflow by infiltration or evapotranspiration. Comprehensive BMPs with water-quality treatment use biological and physicochemical processes to decrease outflow concentrations. The SELDM BMP module also simulates the irreducible minimum concentration by substituting the specified value when simulated BMP effluent concentrations are below the specified value. In this study, a concentration of 0.007 mg/L TP was used as the irreducible minimum concentration (Granato 2014). In SELDM, the flow and water-quality treatment statistics used can result in a net increase in flow or concentrations for some storms, which is consistent with actual BMP monitoring results. In this study, the median of treatment values for the bioretention, composite, detention basin, biofilter (swale), infiltration basin, manufactured device, media filter, retention pond, wetland basin, and wetland channel BMPs from Granato (2014) were used (Table 2).

Table 2 also shows the theoretical median and average for the trapezoidal distribution of each treatment statistic because the average and median are more familiar than the trapezoidal values (Granato 2014). These measures of central tendency are not applied to each event; the actual simulated treatment statistics for each event depend on the correlation to inflow values and, for concentrations, the effect of the irreducible minimum concentration value.

Results

In this study, planning-level estimates of stormflow quality were simulated to examine the potential risks for adverse effects of untreated and treated runoff from impervious areas on receiving-water quality. Impervious- and pervious-area stormflows representing 8 basin-wide IC percentages were simulated; based on local precipitation statistics, each simulation produced a population of TP EMCs for 1,668 randomly generated runoff events over 29 annual-load accounting years (Fig. 3). Commonly used water-quality criteria and risk percentiles were used to examine simulation results.

Effect of Untreated Impervious Runoff on Downstream Water Quality without BMP Treatment

The potential effects of untreated runoff were examined by comparing the risks of exceeding example water-quality criteria of 0.02375 and 0.1 mg/L TP (Fig. 3). Four slices of the simulated TP populations were used to examine the potential effects of

Table 2. Median trapezoidal-distribution statistics used to simulate BMP treatment mechanisms

Treatment	Minimum	Lower bound of MPV	Upper bound of MPV	Maximum	Theoretical median	Theoretical average	Rank correlation to inflow
Flow reduction ratio[a]	0.116	0.548	0.657	1.23	0.639	0.648	0.21
Hydrograph extension (h)	0	0	0	18	5.27	6.0	0.3
TP water-quality treatment ratio[b]	0.056	0.21	0.38	2.158	0.737	0.816	−0.517

Source: Data from Granato (2014).

Note: MPV = most probable value.

[a] Ratio of outflow to inflow volume, correlated to inflow volume.

[b] Ratio of outflow to inflow concentration, correlated to inflow concentration.

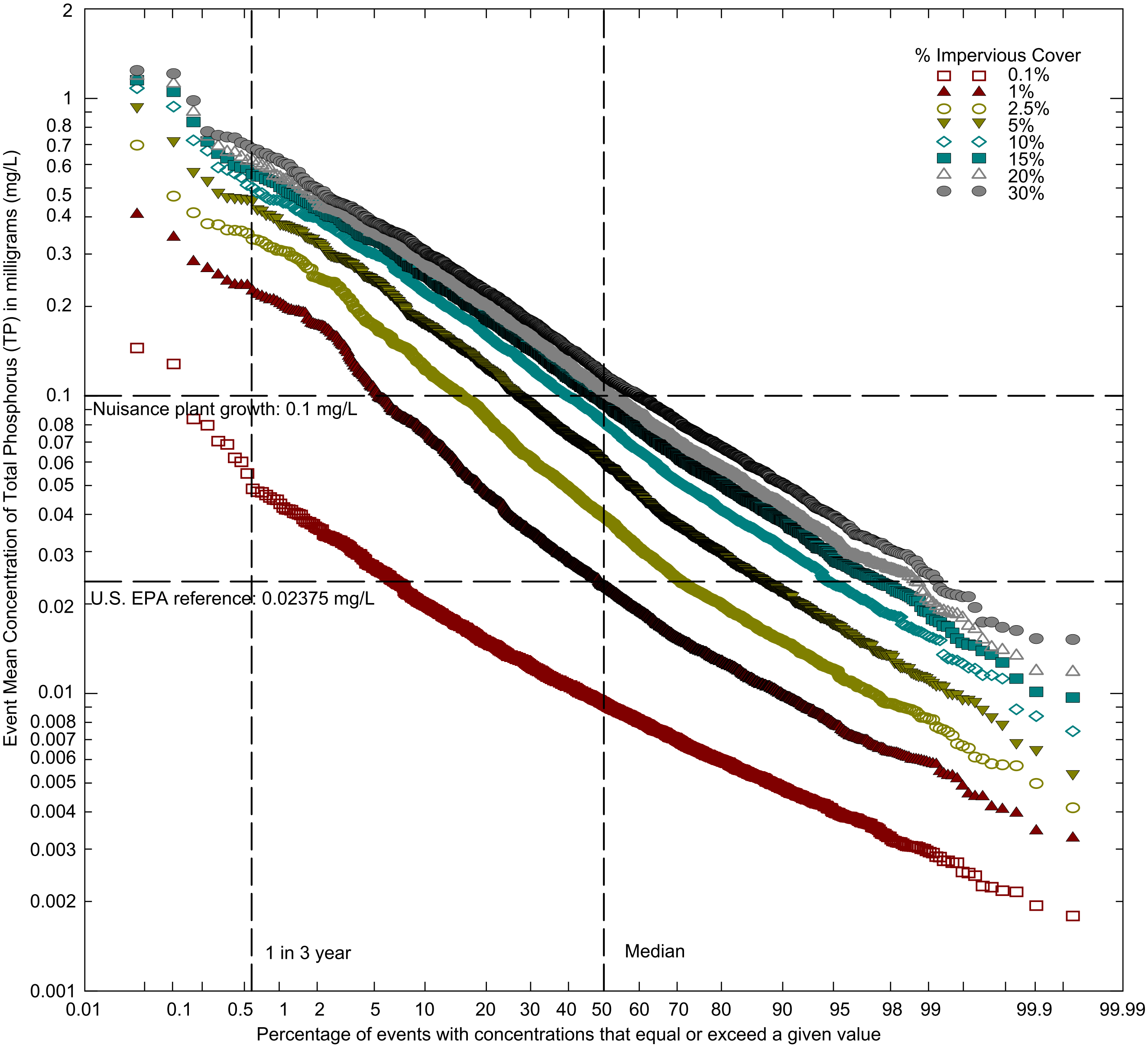

Fig. 3. Simulated 28-year populations of TP concentrations downstream of urban-runoff outlet showing effects of increasing imperviousness compared to selected concentration and exceedance-risk values when median of geometric mean urban-runoff concentration was used.

increasing IC on TP EMCs. The first slice (horizontal dashed line in Fig. 3) represents the USEPA reference condition (which reflects pristine or minimally impacted waters) for TP of 0.02375 mg/L based on the 25th percentile of nutrient data for Ecoregion 59 (USEPA 2000). This criterion is designed to represent conditions of surface waters that are minimally impacted by human activities. The second slice, also shown as a horizontal dashed line in Fig. 3, represents a fixed concentration of 0.1 mg/L (0.1 ppm) TP, which is a TP criterion for preventing nuisance plant growth in streams (USEPA 2017). This fixed concentration was used to examine how the risk of exceeding this threshold changed with variations in the IC percentage. The third and fourth slices of the population (vertical dashed lines on Fig. 3) represent fixed exceedance frequency values of 0.58% and 50%. The exceedance frequency of 0.58% is the once-in-3-years exceedance frequency, which represents the USEPA return period selected as a protective measure to provide for ecological recovery from periods of severe stress (USEPA 2017). The 3-year percentage may be slightly different in this ecoregion depending on the number of storms and annual-load accounting years that are simulated using different random seeds (Granato 2013).

In Fig. 3, the percentage of simulated events that exceed a TP EMC of 0.02375 mg/L ranges from approximately 3.33% of events with an IC of 0.1% to approximately 99.12% of events with an IC of 30%. The percentage of events that exceed a TP EMC of 0.1 mg/L ranges from approximately 0.16% of events with an IC of 0.1% to approximately 59.74% of events with an IC of 30%. The TP EMCs associated with the once-in-3-years exceedance risk range from 0.05 to 0.68 mg/L for the range of ICs from 0.1% to 30%, respectively. The TP EMCs associated with the median exceedance risk range from 0.01 to 0.12 mg/L for ICs ranging from 0.1% to 30%, respectively.

Effect of Treated Impervious Runoff on Downstream Water Quality with BMP Treatment

The potential effects of treated runoff were examined by comparing the risks of exceeding the 0.02375 and 0.1 mg/L criteria (Fig. 4). In these simulations, all runoff from the IC area was simulated as being treated, which may overrepresent the results that may be achieved using structural BMPs in such basins. In Fig. 4, four different scenarios with and without BMPs are shown to illustrate the effects on downstream EMCs in a drainage area with 10% IC. The BMPs that were simulated included a comprehensive BMP (with flow reduction, hydrograph extension, and water-quality treatment) or BMPs with only flow reduction or hydrograph extension alone. The distribution of "natural" or upstream EMCs shown in the figure illustrates the performance of the BMPs relative to upstream water quality. Based on simulation results, BMPs have the greatest effect on decreasing downstream EMCs (compared with no BMP) when downstream EMCs are greater in higher-probability events. For example, with a comprehensive BMP, simulated TP EMCs below the 50th percentile are on average 6.2 times greater than the simulated natural background EMCs compared to EMCs above the 50th percentile that are on average 4.9 times the natural background concentration. Hydrograph extension and flow reduction alone decreased downstream EMCs compared to the simulations without BMP treatment, but not as effectively as with a comprehensive BMP. The BMPs with only hydrograph extension were slightly more effective than BMPs with only flow reduction, decreasing EMCs to an average of approximately 10.4 times the natural upstream EMCs. Flow reduction decreased EMCs to an average of approximately 11.2 times the upstream EMCs.

The simulations also indicate the potential for load reduction. Hydrograph extension BMPs alone do not effectively reduce downstream loads of TP because hydrograph extension alters the timing

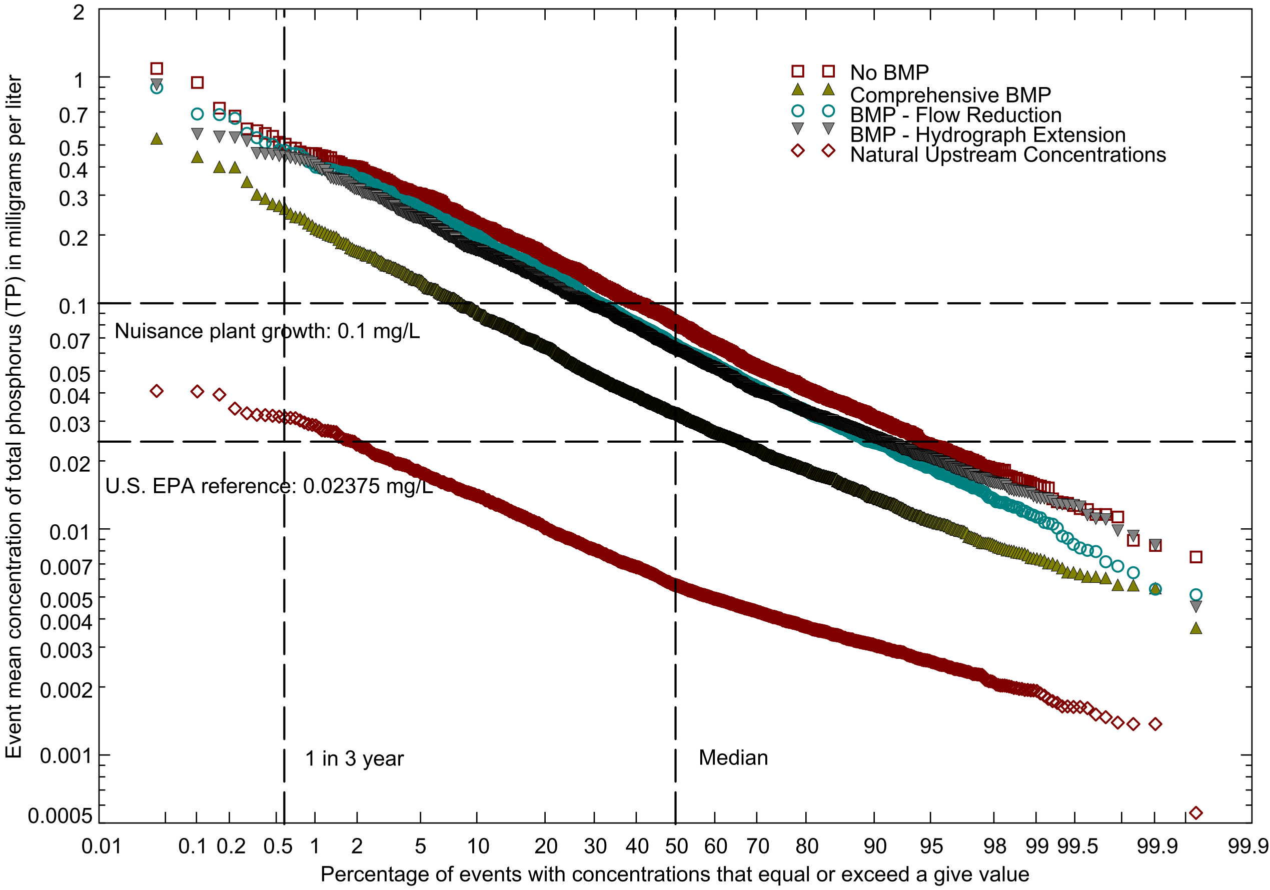

Fig. 4. Scatter plot showing potential effect of stormwater best management practice (BMP) treatment variables, including flow reduction, hydrograph extension, and water-quality treatment, on downstream event mean TP concentration (mg/L) for 10% IC if IC is 10% and all IC runoff is treated.

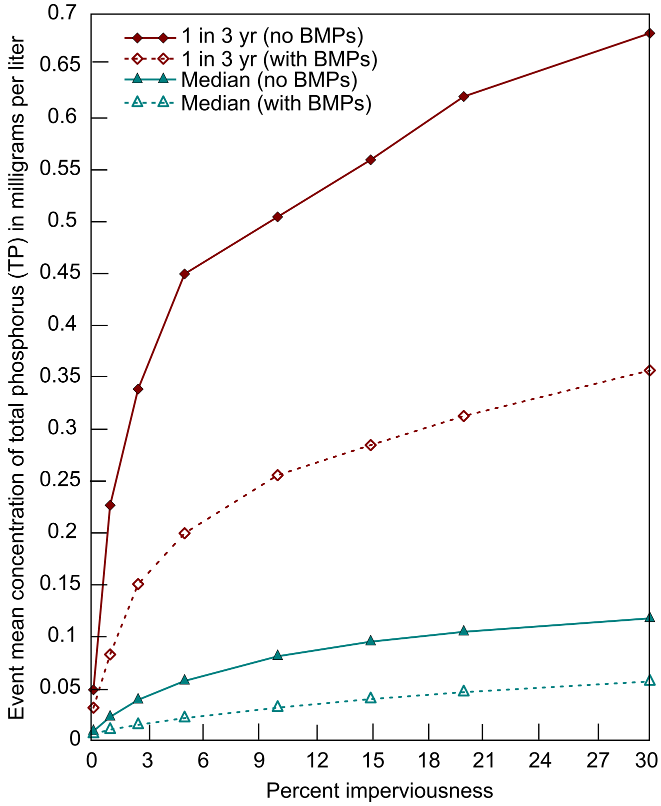

Fig. 5. Event mean TP concentrations at median and 1 in 3-year risk percentiles simulated using median of geometric mean urban-runoff concentration with increasing imperviousness. BMP values indicate simulated concentrations that result from flow reduction, concentration reduction, and hydrograph extension for all IC runoff.

of flow but not the total mass load of urban-runoff constituents to the stream. BMPs with flow reduction decrease the total amount of flow to the stream and therefore decrease the long-term average annual mass load of TP to the receiving waters from the impervious area by 31%. With a comprehensive BMP (one that includes hydrograph extension, flow reduction, and water-quality treatment), long-term average annual runoff loads from the impervious area were decreased by 55% compared to no BMP.

Fig. 5 shows the simulated effects of BMPs on TP downstream EMCs at the 0.58% (once-in-3-years event) and 50% exceedance frequencies with increasing IC. The simulated BMP results shown in this figure include the effects of the hydrograph extension, flow reduction, and water-quality treatment statistics described in Table 2. The downstream concentration at the 0.58% exceedance frequency is 46% lower in the BMP simulations than the untreated simulations. BMPs have a similar effect on downstream EMCs at the 50% exceedance frequency, decreasing downstream EMCs on average by 49%. Generally, the greater the IC, the greater the positive effect of the BMP on decreasing downstream EMCs.

Discussion

The results of these planning-level numerical experiments provide general information that can be used to help inform land- and water-resource management decisions. In general, if TP concentrations are used as an indicator for adverse effects of runoff on stream biota, the results of these simulations are consistent with widespread observations of increasing ecological degradation with increasing development (Arnold and Gibbons 1996; Paul and Meyer 2001; Schueler et al. 2009). The simulated population of stormflow EMCs immediately downstream of the impervious-runoff inputs are shown in Fig. 3. Receiving-water EMC populations are substantially different when IC values are low and converge for each risk percentile as IC increases above 10%. Fig. 5 indicates that the selected risk-based EMCs increase proportionally to the logarithms of imperviousness; the largest rate of change in these EMCs occurs when IC values are low. Many hydrological processes are multiplicative; the loads from each event are the product of precipitation, runoff coefficients, area, and concentrations. Therefore, one may expect a power-law relationship to emerge (Di Toro 1984; Novotny 2004). Because the IC was simulated as directly connected impervious area, the results of these numerical experiments indicate the potential effect of completely disconnecting a portion of the existing IC areas. Assuming that the runoff is untreated, comparison of the results from one IC percentage to another indicates the potential effect of that disconnection. For example, the various metrics presented in these figures show very little improvement when IC is reduced from 30% to 20%, modest improvement when IC is reduced from 20% to 10%, and major improvement when IC is reduced from 10% to 1%. If disconnection and BMP treatment of the remaining runoff can be implemented, then better results can be expected. For example, in Fig. 5, comparison of the untreated downstream concentration at 20% IC (0.62 mg/L) with the treated downstream concentration at 10% IC (0.26 mg/L) indicates a 58% decrease in downstream EMCs at this risk level. Other studies have evaluated ecology and water-quality data from watersheds of similar percentage imperviousness with varying levels of connectivity and have concluded that disconnection of impervious areas does decrease the negative effects on downstream ecosystems (Baruch et al. 2018; Blaszczak et al. 2019).

Comparison of results with and without BMP treatment indicates the potential improvements in downstream EMCs if different BMP treatment mechanisms are used. Results were simulated with the median of category-median treatment statistics from Granato (2014) to represent what might be achievable in a stream basin where various BMPs of various ages and effectiveness are used to treat all impervious-area runoff. Although some BMP types may provide better or worse performance than the simulated generic BMP, it is important to note that it is unlikely that the entire watershed imperviousness would be treated. Therefore, results indicate that hydrologic treatment methods (hydrograph extension or flow reduction) have a limited effect on reducing downstream EMCs, but combining the effect of these mechanisms in a comprehensive BMP with modest water-quality treatment may, if used extensively, result in substantial decreases in downstream EMCs (Fig. 4). For example, in a drainage basin with 10% IC, a comprehensive BMP can decrease downstream EMCs by 61% compared to no BMP. The BMPs with only flow reduction or flow extension can decrease downstream EMCs by 20% and 26%, respectively. However, hydrograph extension and flow reduction also may reduce adverse effects of runoff on receiving water attributable to channel degradation (Walsh et al. 2005).

Although two criteria concentration values have been used with simulation results to discuss the potential for adverse effects of runoff on receiving waters as a function of IC and BMP treatment, the results of these simulations, when compared to commonly used biological thresholds, may indicate that these criteria are too stringent for application to short-term TP EMCs. Water-quality criteria were initially developed for application to the effects of wastewater discharges during low-flow periods when dilution was minimal (Peavy et al. 1985); they were not designed for regulating periodic stormflows. The simulated stormflow from undeveloped areas shown in Figs. 3 and 4 indicates that the proposed nutrient criterion of 0.02375 mg/L (USEPA 2000) is unobtainable for stormwater runoff in the simulated basin if a 3-year recurrence interval (approximately 0.58%) is used (Fig. 3). If IC is simulated as 1%, then approximately 50% of EMCs exceed this value. If IC is simulated as 10%, then approximately 95% of EMCs exceed this value. If the commonly used criterion of 0.1 mg/L TP is used with a 3-year recurrence interval, then only the natural (Fig. 4) or minimally developed (Fig. 3) runoff-quality populations meet this criterion at the specified risk. The exceedance risks for a 5% and 10% impervious basin increase to approximately 28% and 35% of EMCs, respectively. If the simulated population of stormflow EMCs with the impervious threshold of 5% is used to evaluate a potential 3-year TP criterion for stormwater, then Fig. 3 indicates that an EMC of approximately 0.45 mg/L may be protective if 5% IC is a lower threshold for the adverse effects of runoff on the aquatic ecology (Schueler et al. 2009).

The objective of this study was to simulate stormwater quality with available data and statistics as a numerical experiment to examine relations between IC and receiving-water quality. SELDM is a lumped-parameter model designed to provide planning-level estimates of storm event flows, EMCs, and loads; planning-level estimates are recognized to include substantial uncertainties (Granato 2013). SELDM is not calibrated in the traditional sense by matching a historical record; each analysis is constructed using representative input statistics. Because detailed long-term EMC monitoring data collected upstream, at stormwater outfalls, and downstream from those outfalls are not widely available, regional and national data were used to simulate conditions at a hypothetical site. In these analyses, hydrologic, water-quality, and BMP treatment statistics from hundreds of storm events were used to simulate conditions at the hypothetical site of interest. Without long-term site-specific data, however, it is difficult to quantify the combination of statistics that may best represent conditions at a given location. Therefore, simulated results are not expected to be predictive for any specific location. The simulated downstream concentrations with urban runoff may be elevated because the entire volume of runoff is introduced at the mixing point in a lumped-parameter model. Moore et al. (2004) calculated an instream annual-average half-life value of 1.5 days for TP, ascribing the reductions to settling and biological uptake. If this half-life value is used with an assumed stormflow velocity of 0.3048 m/s (1 ft/s), approximately 84% of TP discharged at the basin divide would reach the simulated point of interest. However, instream attenuation may not be substantial during runoff events. The simulated concentrations are EMC values; a greater proportion of within-storm values may exceed commonly used 1-h criteria specifications (USEPA 2017).

Conclusions

Biological studies consistently demonstrate correlations between IC and ecological degradation. The literature indicates that there are many confounding variables that vary by orders of magnitude and negative ecological changes occur along a continuum of increasing total imperviousness, where negative impacts are seen typically around 5%–20% total impervious area (Arnold and Gibbons 1996; Brabec 2009; Paul and Meyer 2001; Schueler et al. 2009). The adverse effects of runoff on receiving-water quality are postulated as a driving factor for the observed degradation in these studies, but robust long-term stormflow-quality data sets quantifying upstream, runoff, and receiving-water concentrations are not readily available. This paper presents the results of a planning-level numerical experiment to examine relations between IC and receiving-water quality. The Stochastic Empirical Loading and Dilution Model (SELDM) was used with available local, regional, and national statistics to simulate a population of stormflows and event mean concentrations (EMCs) from undeveloped areas and developed impervious areas (with and without stormwater treatment) to calculate receiving-water EMCs at a hypothetical discharge point in southern New England.

If the USEPA regulatory threshold of 9% IC for New England is protective of aquatic life, then simulation results indicate that the example water-quality criteria for TP may be too restrictive for application to stormflows. However, it should be recognized that ecological responses occur over a continuum of IC values (Brabec 2009; Schueler et al. 2009). None of the simulated receiving-water EMC populations meet the USEPA 0.02375 mg/L reference concentration for the Northeastern Coastal Zone ecoregion at the 3-year return risk, and more than 50% of EMCs exceed this value if upstream IC exceeds 1%. Only the simulation using an impervious value of 0.1% produced instream concentrations below the 0.1 mg/L criterion at the 3-year return risk. The simulations for the basin with 1% impervious area produced 3-year return risk concentrations that were more than double the 0.1 mg/L criterion. Simulated results indicate that these criteria are unobtainable even if all impervious-area runoff is treated using structural BMPs, which is highly unlikely for most basins. If measured stormflow concentrations are used to identify impaired waters in places where the streamflow ecology is not impaired, then available resources may be misallocated. In this paper, these existing criteria were used as a framework for discussion. However, the patterns of simulated EMCs are more consistent with observed patterns in ecological studies than with the application of these criteria values.

Results of the simulations indicate the magnitude of relations between IC, runoff quality, and the potential for impairment. The simulation results indicate that receiving-water EMCs increase proportionally to the logarithms of IC toward maximum values for each risk percentile. Concentration values converge as IC increases above 10%. Increasing IC in previously undeveloped basins results in greater changes to water quality compared to increasing IC in previously developed basins. This relationship is consistent with the multiplicative nature of many hydrologic processes (Di Toro 1984; Novotny 2004). A similar result was observed in water-quality data collected from several watersheds in the Mid-Atlantic Piedmont area of the United States, where greater increases in specific conductance were associated with incremental increases of low (0%–4.5%) IC (Baker et al. 2019). Because of this pattern, results indicate that efforts to preserve undeveloped stream basins may be more effective than efforts to remediate conditions in highly developed basins. Widespread implementation of structural treatment leads to the greatest instream concentration reductions in the more impervious basins because a larger proportion of the downstream flow is being treated. However, resulting instream concentrations are well above current water-quality criteria with or without BMP treatment, even at a simulated IC value as low as 2.5%. Thus, these water-quality simulations indicate that urban-intensification strategies may be more effective than efforts to manage stormwater runoff from urban sprawl for reducing adverse effects of runoff on receiving waters in southern New England.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies (https://doi.org/10.5066/P9K0Y7XR).

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