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Optimization of Stormwater Filtration at the Urban/Watershed Interface

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Environmental pollution from cities is a major ecological problem attributed to contaminated runoff from nonpoint sources. The U.S. Environmental Protection Agency's guidance on implementation of total maximum daily loads (TMDL) does not adequately cover methods to improve waters impaired by nonpoint sources. To comply with TMDLs, cities may install filters in curb inlets, or use other Best Management Practices (BMPs). We tested 10 different filters and found their effectiveness in retaining pollutants ranged from 0 to >90%, depending on combinations of pollutant types (metals, pathogens, and total suspended sediments (TSS)) and filter materials. Hence, the decision to deploy filters into curb inlets must consider land use patterns associated with specific categories of pollutants generated within cities. We developed a geographic information system (GIS)-enabled model for estimating and mitigating emissions of pollutants from urban regions into watersheds. The model uses land use categories and pollutant loadings to optimize strategic placement of filters to accommodate TMDLs. For example, in a city where the landuse pattern generates 4×10^6 kg of TSS, 55 kg of Cd, and 2×10^3 kg of Zn per year into 498 curb inlets that discharge into a sensitive watershed, the optimized placement of 137, 92, and 148 filters can achieve TMDL endpoints for each pollutant, respectively. We show further that 158 strategically placed filters effectively meet the requirements simultaneously for all three pollutants, a result at least 5 times more effective than random placement of filters.

Introduction

Section 303(d) of the 1972 Clean Water Act (CWA) requires states, territories, and authorized tribes to generate a list of water systems that remain impaired after identifiable point sources of pollution have installed remediation technology (*1*). These jurisdictions must develop action plans to improve water quality based on total maximum daily loads (TMDLs) that mandate maximum annual pollutant loading allocations (LAs) to impaired waterbodies. The 1987 CWA Reauthorization, 1990s Coastal Zone Act Reauthorization Amendments, and litigation involving CWA section 303(d) and TMDLs, have began to address deficiencies in the coverage of nonpoint sources of pollution by the otherwise effective National Pollutant Discharge Elimination System (NPDES) (*2*, *3*). The implementation of LAs from nonpoint sources can occur through a wide variety of regulatory, nonregulatory, or incentive-based programs or through voluntary action by stakeholders (*4*).

The complexity of managing stormwater is matched only by the complexity of urban pollutant mixtures emanating from an equally complex array of sources. For example, an estimated 19 million residents and 60 million visitors to California's coastal communities account for almost $10 billion of the annual state economy, with fishing and water-intensive agriculture providing an additional $28 billion (*5*, *6*). The U.S. Environmental Protection Agency (USEPA) approved California's Section 303(d) list, including 684 water bodies (30% of monitored systems), on July 25, 2003 (*1*). The most pronounced gap in recent efforts to manage urban stormwater runoff is the lack of coordination of linkages between land use and pollutant loadings in the technical design and implementation of Best Management Practices (BMPs) for stormwater remediation (*7*−*10*).

Installation of filter inserts into storm drains at street level is a convenient BMP for controlling urban runoff due to its potential specificity and ease of placement. However, there has been little research linking the material composition of these filters to specific pollutant loadings under different land use conditions (*11*). Municipalities currently have an assortment of technologies for reducing runoff according to the text of TMDL regulation and to the “maximum extent possible” according to NPDES permit guidelines (*12*−*14*). However, the ambiguity of the text has led to differences in the adoption of various BMPs by cities contributing effluent to the same watershed, and there are no comparative studies on the effectiveness of various technologies across BMPs. Here, we analyze the placement of filters at the interface of urban runoff and stormwater drainage systems. Catch basin filter inserts employ a variety of adsorbent materials designed to retain pollutants, but there is uncertainty on their ability to remove a mixture of specific pollutants in urban runoff (*15*−*18*). In theory, no single product can effectively deal with various categories of pollutants with acceptable efficiency and at affordable installation and maintenance costs. Therefore, cities need to conduct extensive preliminary investigation on the capacities of different filters, their pollutant removal efficiencies, and the best location for each category of filter, depending on land use patterns.

For our case study, three TMDLs are established for Newport Bay and its tributary San Diego Creek at the boundary of the City of Costa Mesa: toxics (metals and pesticides), sediments, and nutrients (P and N). Additionally, there is a TMDL for fecal coliform within Newport Bay (*19*). Our research focused on metals, sediment, and fecal coliform TMDLs, and the potential for meeting the TMDL limits by using storm drain filter inserts throughout the city.

We address two important goals: (i) The generation of data on pollutant removal efficiencies for various filters and demonstration of how such data can be used to support the optimization routines, and (ii) Development of a methodology for optimizing the employment of structural BMPs across a city, using a model that couples a GIS-based runoff generation module with a linear programming-based optimization routine. The model does not account for potential variations in filter performance due to antecedent dry and wet days, hydraulic peaks, and shear factors, which are better evaluated under field conditions, subject to technical and liability constraints imposed by cities such as Costa Mesa,

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California, which we used to demonstrate the optimization process.

Experimental Section

Effectiveness of Filters. The characteristics of the 10 filters tested in this study are described in the Supporting Information, Tables A and B. The filters were pre-washed and saturated with sterile deionized water prior to introducing pollutants.

To bacterial retention, we used *Escherichia coli* O157:H7 cultivated in Luria−Bertani (LB) broth at 37 °C to represent fecal coliform bacteria, designated as such throughout the text. Cells were harvested, washed twice, and re-suspended in phosphate buffered saline (PBS) at 100−800 CFU ml^{-1} in increments of 100 CFU mL^{-1}. Bacterial suspensions were applied to test filters at a flow rate of 3 L min^{-1}. Each bacterial concentration was tested in duplicate, and triplicate samples of the effluent were serially diluted in PBS prior to enumeration by viable assay on LB agar.

Metals (Cd, Cu, Pb, Zn, and Se) were tested at concentrations (0.01−0.4 mg L^{-1}) based on the respective acute dissolved TMDL limits or monitored values for the watershed (*20*, *21*). Each metal was tested in duplicate at a flow rate of 3 L min^{-1}. 250 mL of the effluents were collected and adjusted to pH 2.0 with nitric acid prior to the determination of metal concentrations using EPA method 6010B: Inductively Coupled Plasma-Atomic Emission Spectrometry.

We tested 8 concentrations of total suspended sediments (TSS) in two duplicate batches. Initially, we tested 0.6−4.8 g L^{-1}, and all but one filter retained 100% of TSS in this range. Therefore, we tested higher TSS concentrations covering 6−48 g L^{-1}, which is reasonable considering that the highest monitored suspended sediment concentration within the watershed as 28.8 g L^{-1} (*22, 23*). The higher TSS concentrations did not attain cake filtration, thus particle removal mechanisms fall within the range predicted by clean bed filter theory, straining for larger particles and adsorption for finer particles (*24).* The TSS effluent concentrations were estimated according to Packman et al. (*25*). We used sand with a 40−100 mesh size (420−149 μm) and a model 966 Orbeco-Hellige portable turbidimeter. Similar particle size represented up to 15% of monitored TSS in the watershed in April 2005 (*29*) and constitute 26% of surface runoff determined by Lau et al. (*14*). The correlation between TSS and turbidity was strong ($R^2 = 0.94$) and described by Log TSS = [Log (NTU^{-1})/1.50] + 0.63.

TMDLs. The TMDLs established for San Diego Creek and Newport Bay are reported in the Supporting Information Table D. The TMDL target requires acute fecal coliform concentrations to be less than 4 CFU mL^{-1} and chronic concentrations (5-day mean) to be less than 2 CFU mL^{-1} (*19*). Monitoring between years 2001 and 2005 revealed spike concentrations within the Newport Bay greater than 230 CFU mL^{-1} (*26*). Under current guidelines the LAs are scheduled to allow unimpaired recreational use by December 30, 2014 and shellfish harvesting by December 30, 2019.

The sediment and toxics TMDLs for the watershed were predicated by a 1997 litigation; Defend the Bay, Inc. v. Marcus; N. D. cal no. C 97-3997 MMC (*22*). The sediment TMDL was completed by the USEPA in 1998 and amended by the State of California in 1999. The TMDL requires cities within the watershed to reduce sediment loads by 50%—from 127 006 tonnes of sediment per water system to 63 503 tonnes—within 10 years (*23*). The metals TMDL was promulgated by the USEPA in 2002, with the caveat that dissolved saltwater TMDL for cadmium applies only to the Upper Newport Bay and not to the Lower Newport Bay (*21*).

To evaluate filter performance toward meeting water quality standards, we compared average pollutant retention measurements to the ratio of TMDL−LA and the highest monitored pollutant concentrations in the watershed (Supporting Information Table D).

Integrative Model of Land Use and Filter Optimization. To optimize the implementation of city-scale effluent filtration, we developed a conceptual framework that integrates land use, filtration effectiveness, and regulatory or managerial options in an analytic geographical information system (GIS) model. The model consists of five components associated with urban stormwater hydrologic processes: (a) *pollutant source residual estimation*, represented as a raster GIS layer such that the modeled watershed is divided into an array of cells, with cells representing an average mass loading from nonpoint sources particular to the corresponding land use type; (b) *surface flow pollutant distribution*, to capture topographic constraints on the distribution of pollutants generated in step one, also represented in raster format; (c) *inlet pollutant entry estimation*, calculates the mass loadings that enter the stormwater network through structural features such as curb inlets, represented as node features within the GIS framework; (d) *network flow pollutant distribution*, which models the transport of pollutants specifically through a city's stormwater system and is represented as a topologically integrated line feature; and (e) *outlet pollutant discharge estimation*, based on pollutant mass loadings that are returned to receiving waters through specific discharge outlets or the termini of the stormwater network.

To test the model, we obtained datasets from the City of Costa Mesa, including categorical land use zones, transportation, and stormwater network, including topological information, flow direction, and associated structural features such as location of curb inlets and drainage outlets. We relied on the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS 3.1) hydrologic model developed by the USEPA (*27*) as the template for customizing GIS (ArcView 3.3 and ArcGIS 9.0). We also used BASINS for pollutant source residual estimation based on unit area loads (UAL) representing the mass of a given pollutant generated from a given area and type of land use during a specified time interval ($\mathrm{kg/km^2/year}$). Mass loading of the pollutant into the environment is modified by the runoff coefficient (*30*).

$$R_{\mathrm{vu}} = 0.00197 + (0.2286 \times I_{\mathrm{u}}) \qquad (1)$$

Where R_{vu} is runoff coefficient for land use type u, [mm run/mm rain] and $I_{\mathrm{u}}$is the percent imperviousness, and

$$Lp = \sum u\ (P \times P_{\mathrm{j}} \times R_{\mathrm{vu}} \times C_{\mathrm{u}} \times A_{\mathrm{u}} \times 0.4992) \qquad (2)$$

Where Lp is pollutant load, [kg], P is precipitation, [mm yr^{-1}], P_{j} is ratio of storms producing runoff, R_{vu} is runoff coefficient for land use type u, [mm run/mm rain], C_{u} is event mean concentration (EMC) for land use type u, [mg L^{-1}], and A_{u} is area of land use type u, [km^2].

The city's land use pattern was converted from a vector-based GIS layer to a raster or ESRI GRID dataset at a resolution of 10 m. Pollutant loadings are estimated for each 10-meter pixel cell in the raster dataset. For example, the annual generation of total suspended sediments (TSS) was based on an average of 289 mm of annual rainfall and an average 85.0% of storms producing runoff (*31*) Please refer to Table E within the Supporting Information for exact EMCs.

A 10-meter resolution digital elevation model (DEM) provided by the United States Geological Survey (*32*) was used to model the flow of pollutants across the land surface. The raw digital terrain model was corrected using the U.S. Army Corps of Engineers Geospatial Hydrologic Modeling Extension or HEC−GeoHMS (*33*). The extension's *fill* function was used to create a depression-less terrain model (i.e., a terrain model relatively free of aberrant pits or depressions) and we applied a *burning* technique to impose open drainage channels and streets onto the landscape so as to account for the urban features that influence water flow. We also used ArcInfo Workstation's *flowdirection* function to compute a grid representing the direction of flow between every cell in the DEM grid. Last, we computed the accumulated concentration of pollution across the landscape using a *flowaccumulation* function together with the flow direction and pollutant residuals layers developed earlier. The output of the surface flow distribution model is a continuous raster grid, with each grid cell representing an estimated annual distribution or accumulation of mass loadings; greatest accumulations of pollutants occur along roadways, natural channels, reservoirs, and other physical depressions.

We adapted the city's inlets GIS point layer to compute the likely amounts of pollutants entering the stormwater network through curb inlets. Mass loading estimates were inferred from the value of the 10-meter pixel associated with each of the city's curb inlets and the total pollutant loadings accumulated within a specified proportion of the sub-basin flowing into the inlet. Pollutant mass loading estimates by curb inlet were conceptually transported through the city's stormwater infrastructure using standard ArcGIS network analysis tools. The modeling of network flow allows for estimation of total pollutant discharge by outlet. The portion of the City of Costa Mesa's stormwater network, which discharges directly into Newport Bay and the Newport Bay Ecological Reserve, is comprised of 498 curb inlets and extends approximately 67 km; 52 km of which are open (natural stream, concrete-lined, and open earth) channels and the remaining 15 km are closed (i.e., main, connector, and culvert) channels.

After estimating generation of specific pollutants per land use and modeling their transportation over land surfaces, we next incorporated the results of filter pollutant removal effectiveness. After specific percentile reduction of the pollutants, flow was modeled through stormwater networks, and total filtered pollutant discharge was aggregated by stormwater outlet. Costa Mesa's GIS dataset is comprised of 42 outlets, the majority of which discharge into natural swales or retention basins within the city, but some discharge directly into sensitive watersheds such as San Diego Creek, Newport Bay, and the Upper Newport Bay Ecological Reserve (UNBER) located at the confluence of the two and incorporating 752 acres of the upper bay area. We used mixed integer programming (MIP) to explore various placement optimization routines to identify filter insert system strategies throughout the city, in this case, the optimization models calculate the minimum number of filters needed to comply with TMDL requirements given the mass loadings into each curb inlet and the average removal efficiencies of the filter inserts for each pollutant category. The LPSolve IDE version 5.5 mathematical package was used to calculate solutions to the different optimization scenarios (*34*).

Results and Discussion

Commercial availability of filters and ease of installation at curb inlets make them appealing to cities that wish simply to achieve the goals of TMDL regulatory specifications and to reduce pollutant loading "to the maximum extent possible". However, it remains unrealistic for large cities with typically more than 1,000 curb inlets to fit every inlet with filters and expect uniform performance, because there is a large selection of filters with a variety of features, which complicates the decision process. There are two important questions: (1) can filters achieve quantitative water quality goals of TMDL implementation and (2) can this be done incorporating strategic placement of filters to eliminate the necessity of a filter per catch basin, reducing a city's cost and maintenance. To answer these questions, we evaluated 10

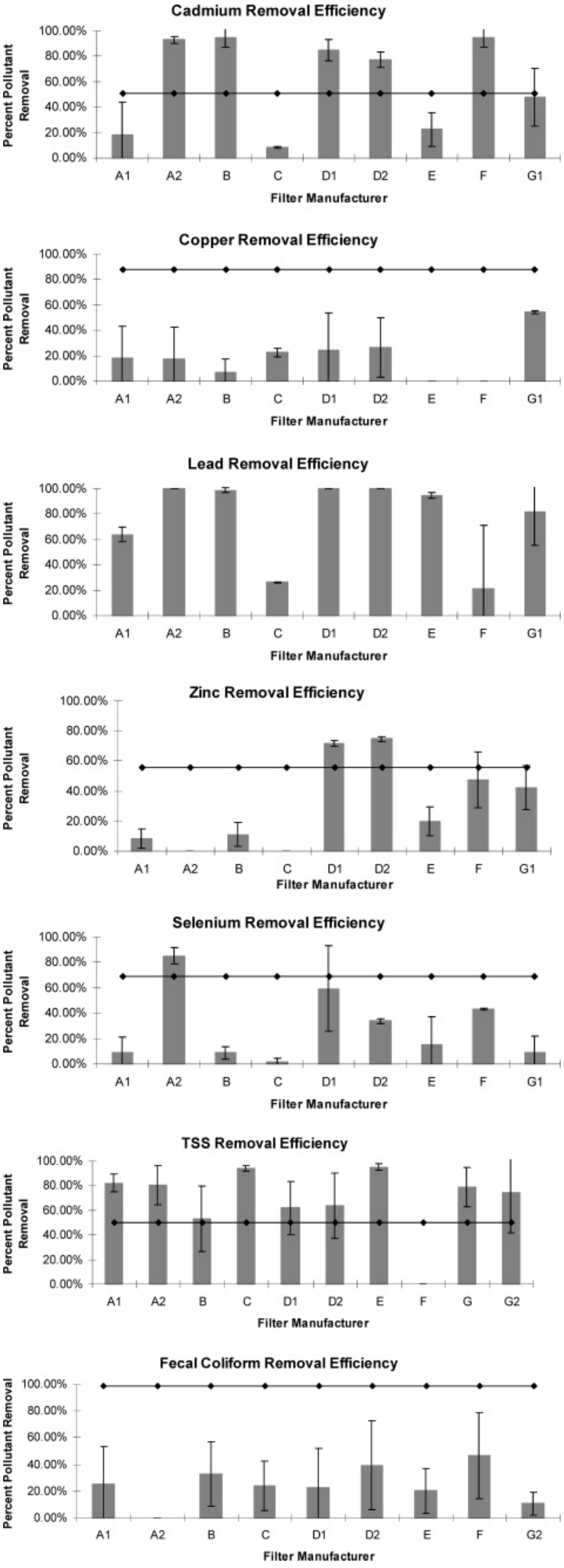
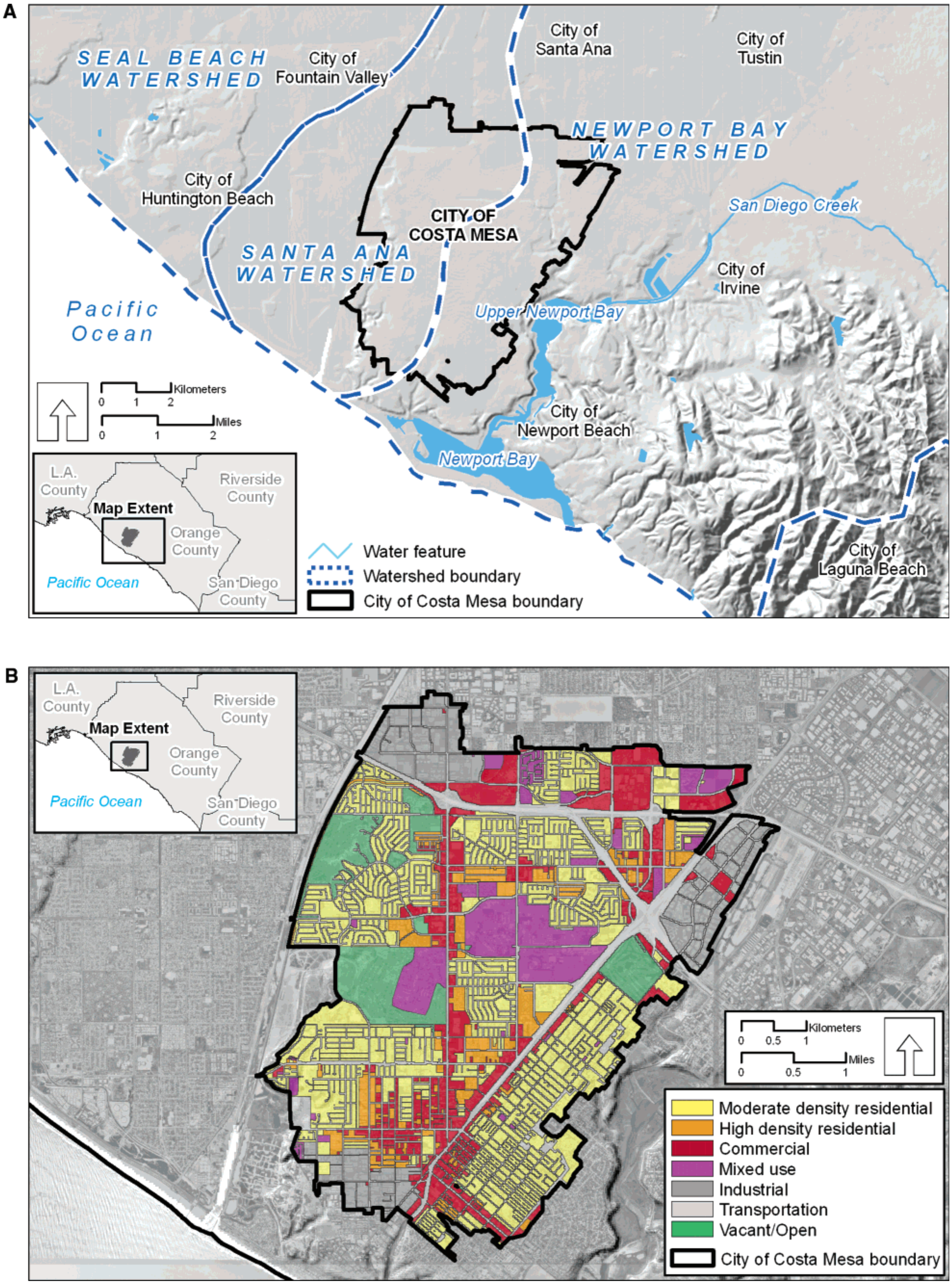
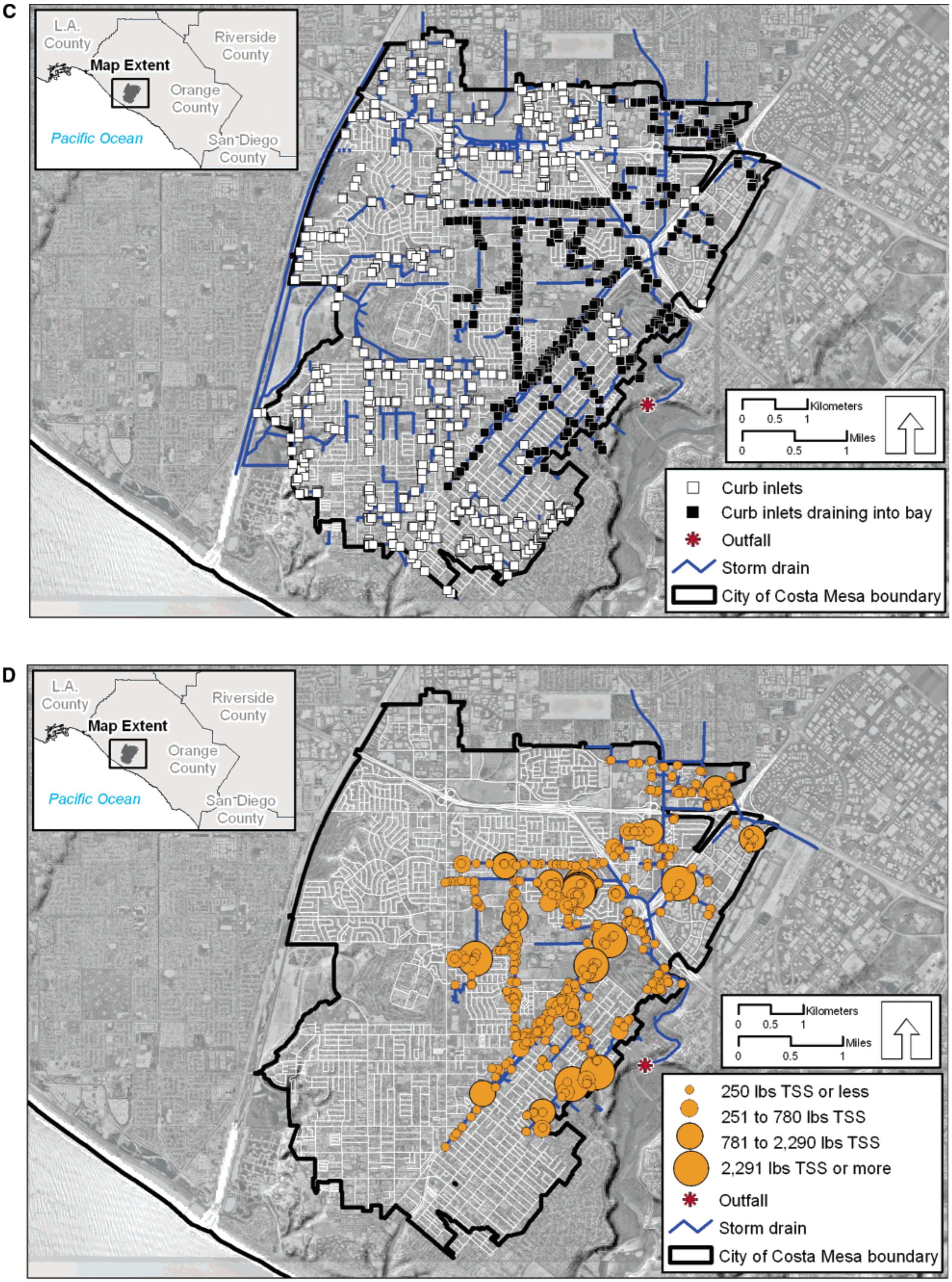


FIGURE 1. Pollutant removal effectiveness for each filter and pollutant. Line represents targeted TMDL reduction (TMDL−LA/highest monitored value) and bars represent actual removal efficiencies of each filter ± SD. The highest monitored Pb value was less than the TMDL.



commercially available products for their effectiveness in filtering different categories of pollutants generated in cities. Furthermore, we integrated the data on filter performance into a GIS model of land use patterns linked to pollutant generation and transport in the case study city of Costa Mesa.

Catch Basin Filter Properties. There are two main types of filters: box and sock (Supporting Information Tables A and B). Box filters are rigid containers of filtration media. Influent runoff percolates through the media, continuing into the storm drain. Sock filters are fabric sheets directing



influent runoff into a central pocket, typically including a sewn-in polymer fabric. Stormwater permeates the fabric and leaches through to the storm drain.

Laboratory testing provided the necessary conditions for evaluating best-case-scenarios for filter performance without the liability issues associated with deliberate release of pollutants such as toxic metals and bacteria in a field setting. Conversely, we could not analyze high flow rates that might be encountered in first flush situation, but these are rare in the case study watershed. Each pollutant was tested at

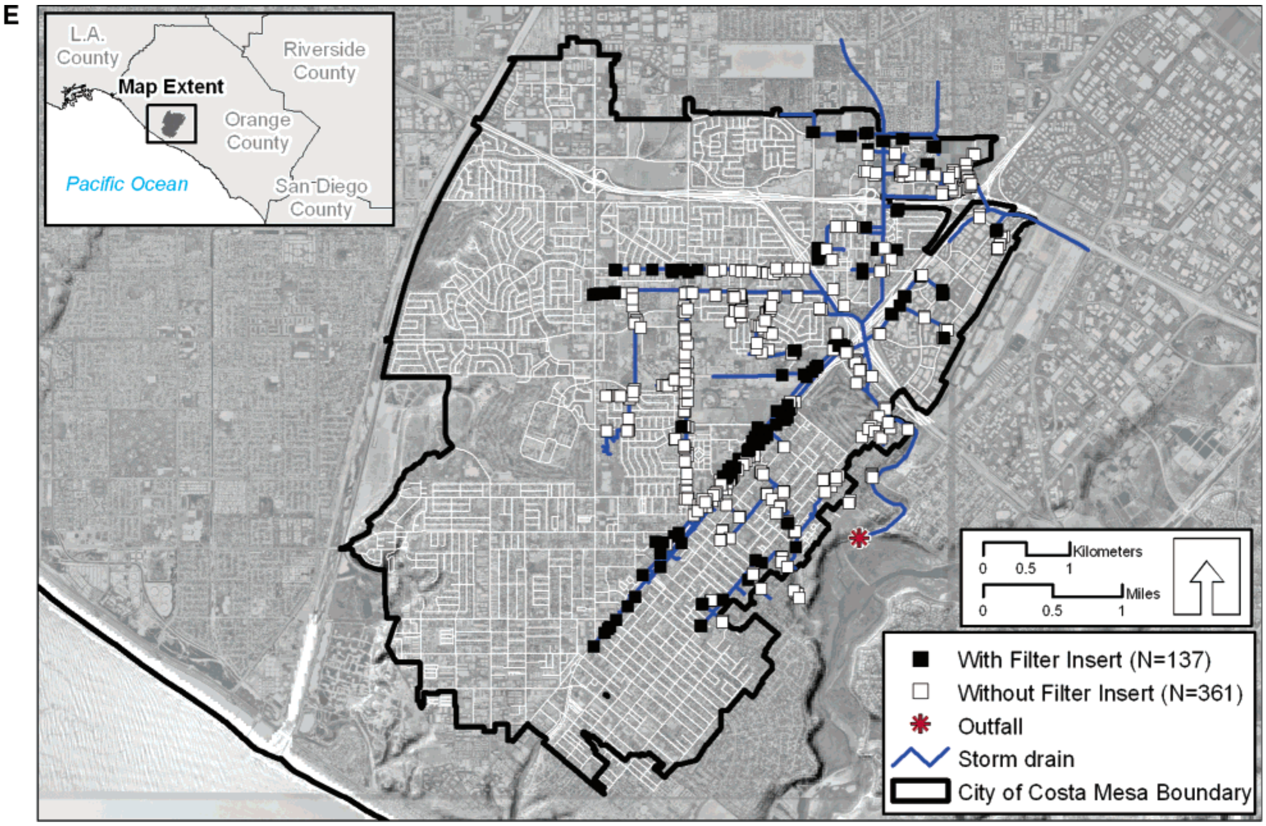


FIGURE 2. Panel A: San Diego Creek and Newport Bay watersheds. Panel B: Landuse pattern for the case study City of Costa Mesa Panel C: Location of curb inlets for the entire city. Panel D: Pollutant loading allocation for suspended sediment discharging into the Upper Newport Bay Ecological Reserve from the city's 498 curb inlets. Panel E: Optimized placement of filter inserts by curb inlet, combined TSS, Cd ,and Zn TMDL compliance.

concentrations reflecting current TMDL allocations and observed data in the watershed.

Fecal Coliform Removal. The performance of the filters in removing fecal coliform ranged from 0% (standard deviation, 0.0) to 46.6% (SD, 32.4). All filters tested performed below the 98.3% removal efficiency necessary to meet TMDL standards (Figure 1 and Table C, Supporting Information). The highest recorded level of fecal coliform within the Newport Bay, 230 CFU mL^{-1}, is an outlier in the monitoring data; this population density is more than 50 times higher than the required acute TMDL (4 CFU mL^{-1}). A more realistic removal efficiency of 50% is within one SD of the removal mean for five of nine tested filters. For municipalities with a more chronic than acute coliform problem, these results could be beneficial. It was surprising to note the two lowest removal rates were measured for filters that contained known anti-microbial substances (A2 and G2). We re-tested these filters, storing the effluent for a 24 h period before analysis, and the performance of G2 increased to 96.4%, indicating that prolonged contact with the coliform was necessary to activate the anti-microbial activity of the filter material. No such increase in removal efficiency was observed with filter A2. These data imply that filters marketed as having antimicrobial properties are not necessarily more effective in reducing the effluent risk from fecal coliforms than other filter materials.

Metal Removal. Three filters removed less than 7.5% of influent Cu, and no filter removed greater than 55% of this metal. However, for Pb, eight of nine filters tested were within 1.0 SD of removing more than 69.5% and five filters removed a mean value of Pb equal to or greater than 90.0%. The needed removal effectiveness for Pb was not estimated because all data from monitoring programs showed values lower than established TMDL−LA. For Cd, six of the nine filters exceeded the needed removal efficiency (50.6%), with five filters significantly exceeding that amount. For Zn, two filters demonstrated removal effectiveness above the TMDL required 55.7%, and two filters were within one SD of needed removal. Removal of Se was likewise sporadic, with only two filters within one SD of the mean needed removal efficiency.

TSS Removal. All but one filter exceeded the needed removal efficiency for TSS. Filter F was constructed of loosely packed materials which increased the turbidity and TSS of the effluent, exceeding the influent. The remaining nine filters each supported a mean removal rate beyond the determined TMDL percentage. The flow rate used in this study (3 L min^{-1}) may exaggerate TSS removal, but the test conditions are consistent with reasonable dry weather conditions (majority days in southern California) and the beginnings of first flush.

Compliance with Total Maximum Daily Loads. The combined mean effectiveness of the filters met the needed TMDL removal percentage for three pollutants, TSS, Cd, and Zn. Mean Cd removal was 60.1% (50.6% removal required to comply with TMDL); Mean Zn removal of 30.6% + 1.0 SD (29.4%) was greater than the required 55.7%; and the 68.3% mean of TSS removal outpaced the needed 50.0%. In addition, the mean removal of Pb was the greatest of all tested at 74.2% and the filters removed approximately 30% of Se. The filters performed poorly in the removal of Cu (18.9%) and fecal coliform (24.5%), with no single filter removing greater than 55% of these pollutants.

Filters that retained pollutants at values exceeding the necessary concentrations to meet the TMDL standards were considered "high-performing" filters, and the mean pollutant removal values for these filters were used in the model optimization scenarios. Nine of 10 filters tested removed an average of 75.85% of TSS, whereas, only two of those nine

TABLE 1. Estimated Pollutant Mass Loadings into Storm Drains Based on Land-Use Patterns, and the Result of Optimization Modeling of Filter Requirements Based on Data on Average Effectiveness of Filters

	TSS (tonnes/yr)	Cd (kg/yr)	Zn (kg/yr)
sum of mass loadings	4.1×10^3	55.1	2.1×10^3
mean	8.3	0.1	4.2
median	5.5	0.1	2.1
standard deviation	1.5×10^3	20.8	8.0×10^2
minimum	0.0	0.0	0.0
maximum	4.1×10^3	55.1	2.1×10^3
TMDL required removal	2.1×10^3	27.9	1.2×10^3
number of filter inserts needed for TMDL compliance	137 of 498 possible intervention locations	92 of 498 possible intervention locations	148 of 498 possible intervention locations

filters sufficiently removed Zn (73.23%) and five filters effectively reduced Cd concentrations (88.88%).

Model Optimization and Scenario Results. To optimize effluent filtration we investigated potential reductions in TSS, Cd, and Zn by modeling various distributions and applications of filters to curb inlets throughout the section of storm drain network which discharges directly into Newport Bay. The objective functions minimize the number of inserts necessary for TMDL compliance or, more specifically, the minimum number of filter inserts necessary to meet the percentage reductions in TSS, Cd, and Zn noted above.

Figure 2a–d presents the overview map of the urban watershed, the landuse pattern, the location of all 1266 curb inlets within the city's confines, and a 66.8 km section of the City of Costa Mesa's storm drain network that flows into Newport Bay through five discharge points. According to our estimates, more than 4×10^6 kg of TSS, 55 kg of Cd and 2×10^3 kg of Zn currently discharges from these outlets into the bay annually (Figure 2d shows the estimated discharge distribution for TSS). Yet, there is a considerable amount of variation with respect to the mass loadings that flow through each of the 498 curb inlets (Table 1). Because of distinct land use patterns, *where* the city chooses to install filter inserts will affect the total amount of TSS, Cd, and Zn discharged into the receiving water. To illustrate this, we generated the optimized distribution of filter inserts by pollutant type—or the minimum number of inserts needed to comply with the stated TMDL reductions for each pollutant modeled independently (Supporting Information, Figure A). Figure 2e shows the combined optimized placement of filter inserts—or the minimum number of filter inserts necessary to meet the collective requirement of all three pollutants. Strategic placement of only 158 filters can reduce the city's pollutant loading to meet TMDL requirements. The optimization process means that the city needs only to maintain filters in 30% of available catch basins, a major saving in economic and energy expenditure compared to the alternative of blanket installation of filters in catch basins as currently practiced in some municipalities.

Quantitative data on filter effectiveness in conjunction with modeled land use pollutant loadings and stormwater flows suggest curb inlet filters and placement optimization within a city can be combined to meet stringent TMDL–LAs. The approach presented here can be extended to additional BMPs, stormwater dynamics, and cities or watersheds to reduce the impairment of waterbodies due to stormwater pollution. Optimal placement increases cost-benefit ratios by meeting requirements using the least possible number of resources.

Policy Implications. We show here that TMDL attainment requires a rational method for BMP employment. As seen in the case of Costa Mesa, filter inserts prove to be feasible BMPs for meeting TSS, Cd, and Zn standards, but increasingly ineffective when more pollutant TMDLs are added to the list. Moreover, placement of these BMPs across the stormwater network requires a rigorous optimization exercise, in addition to careful selection of filter type for particular sections of the storm drain network, depending on land use patterns and specific pollutant loadings.

We contrast the arguments for deliberative action necessary for effective BMP application with the ad hoc manner that many municipalities currently employ BMPs because of inherent flexibility in the interpretation of federal policy on the control of nonpoint sources of pollution. In their concern over stringent TMDL requirements, city decision makers are implementing BMP strategies with insufficient analysis. For example, adjacent to Costa Mesa is the City of Newport Beach, which decided to install a single type of filter insert in all its street inlets. On the other hand, the nearby City of Irvine is proposing to completely rely on artificial wetlands scattered throughout the city. Reasons for such widely varying strategies are unclear because all three cities contribute to the quality of water in San Diego Creek and Newport Bay.

In conclusion, we strongly advocate the need to combine rational BMP optimization methodologies with empirical BMP effectiveness data, as we have done here. The stringency of TMDLs that are just being developed, suggests that this rational method must also be combined with institutional designs based on collaborative, learning approaches that are sensitive to temporal and spatial changes in urban land use patterns (e.g., see ref *35*).

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Supporting Information Available

Details of the filter inserts used, including fill capacity, cost, and materials; tabulated results of filter tests; TMDL load allocations; and EMCs used in optimization model. This material is available free of charge via the Internet at http://pubs.acs.org.

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