Modeling stormwater mass emissions to the Southern California Bight

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ABSTRACT - Stormwater runoff is perceived as a major source of pollutants that results in adverse environmental effects, but large-scale assessments are rarely conducted. The problem is particularly pronounced in southern California, where 17 million people live in proximity to rapidly developed coastal watersheds. The goal of this study was to make regionwide estimates of mass emissions, assess the relative contribution from urbanized watersheds, and compare pollutant flux from different land uses. A GIS-based stormwater runoff model was used to estimate pollutant mass emissions based on land use, rainfall, runoff volume, and local water-quality information. Local monitoring data were used to derive runoff coefficients; over 1,700 stormwater sampling events were used to calibrate and validate annual loadings. An average rainfall year produced $1{,}073 \times 10^9$ L of runoff, 118,000 metric tons (MT) of suspended solids, 1,940 MT of nitrate-N, 108 MT of zinc, and 15 kg of diazinon. The majority of mass emissions were from urbanized watersheds except for suspended solids, total DDT, and chlorpyrifos. Agricultural areas had the greatest fluxes for pesticides, including total DDT and chlorpyrifos, while open areas typically had the smallest.

INTRODUCTION

Stormwater runoff is perceived to be a large source of pollutant loading, creating multiple ecological effects in receiving waters (U.S. EPA 1995). Stormwater runoff affects the water quality of coastal receiving waters in the Southern California Bight (SCB) (Figure 1). For example, Bay *et al.* (1998) found that stormwater is toxic to marine organisms; Schiff (2000) noted that stormwater alters habitat quality; and Noble *et al.* (2000) found that runoff events increase the frequency that SCB beaches exceed water-quality thresholds of concern.

Numerous sources of potential pollutants in stormwater runoff exist, including contributions from urban activities such as industry, transportation, and residential development or from agricultural activities. This problem is exacerbated in the SCB, where urbanization dominates most watersheds. Over 25% of the nation's coastal population lives in the SCB (Culliton *et al.* 1990). Approximately 17 million people live in the four coastal counties that border the SCB, a number that is expected to grow another 3 million by 2010 (Schiff *et al.* 2000).

Quantification of pollutant inputs from stormwater runoff for large regions, such as the entire SCB, has rarely been attempted. Estimates of stormwater mass emissions in the SCB have occurred largely as the result of special studies (Project 1973; Cross *et al.* 1992). Although stormwater runoff monitoring for mass emissions does occur in some parts of the SCB as part of the National Pollutant Discharge Elimination System (NPDES) permits for

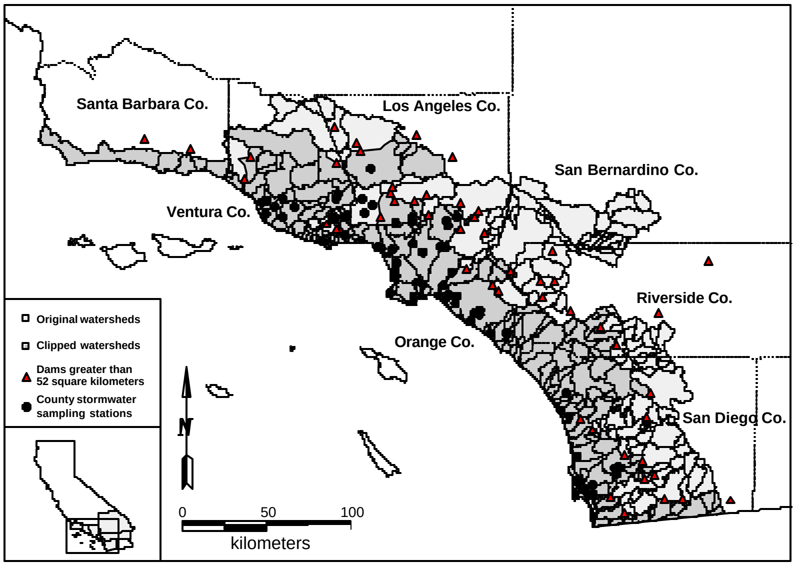

Figure 1. Map of the Southern California Bight watersheds, large dams, and NPDES sampling locations.

municipalities, the monitoring efforts are relatively isolated in their scope and methodology, thereby lacking the integration required to make large regional assessments of stormwater mass emissions. For example, only 5% of the SCB watershed area and 2% of the annual runoff volume were representatively monitored in 1994 (Schiff 1997).

Modeling stormwater mass emissions represents a cost-effective alternative to empirically measuring stormwater mass emissions over regional spatial scales. Unfortunately, modeling runoff mass emissions requires water-quality information for each land use designated in the watershed. Previous modeling efforts have used land use data from the EPA's National Urban Runoff Program (NURP) (Guay 1990) or other regional data sets (Wong, Strecker *et al.* 1997, Escobar 1999, Burian and McPherson 2000). Throughout the SCB, however, an extensive dataset exists for wet weather water quality from specific land uses. Approximately $1.5 million is spent cumulatively on stormwater monitoring efforts in the SCB annually, with a large proportion expended on land-use-specific sampling.

There were two goals for this study. The first goal was to make an estimate of regionwide stormwater runoff mass emissions to the SCB. A stormwater runoff model was developed to make this estimate of mass emissions. The large, locally derived dataset was used to help calibrate and validate the model. The second goal for this project was to utilize the model to assess the effect of urbanized watersheds and determine the relative pollutant contributions from different sources (land uses) within urbanized watersheds.

METHODS

Model Development

Our model to estimate stormwater runoff mass emissions to the SCB was based on a relationship between rainfall and total storm runoff volume with an associated water-quality concentration:

$$\text{Load} = A * i * c * \text{Conc} * k$$

where:

A = Drainage area (km^2)
i = Rainfall (mm)
c = Runoff coefficient (unitless)
Conc = Water-quality concentration (mg/L)
k = constant (units conversion factor)

The model was similar to the U.S. EPA's Simple Method (U.S. EPA 1992) with the exception that the term used to incorporate events that produced no runoff was excluded.

Drainage Areas

Hydraulic unit code (HUC) areas were followed to define the model domain. A geographical information system (GIS) was used to develop these spatial domains. The HUCs were downloaded from a data set created by the Interagency California Watershed Mapping Committee (CAL DEPT FISH GAME 1998). These areas delineated the maximum spatial coverage of runoff that could reach the ocean. Fifteen HUCs were initially used in the SCB region covering approximately 27,380 km^2 that included San Diego, Orange, Riverside, Los Angeles, San Bernardino, Ventura, and Santa Barbara counties.

Watershed areas larger than 52 km^2 upstream of dams were removed from the model domain as represented by the USGS DEM data (USGS 1993) (Figure 1). These areas were chosen based on local knowledge of dam operations and removed to produce a more accurate representation of actual runoff reaching the coastal ocean and reduce bias associated with runoff retention and constituent transformation. Dam information, location, size, drainage area, etc., was obtained from the California Department of Water Resources. After dam removal, 191 watersheds remained in the model domain covering 14,652 km^2 (54% of the original area).

The land use composition within each county was characterized (Table 1). Using data collected from a variety of sources (SANDAG 1993, SCAG 1995, ESCOBAR 2000). Land use resolution by each source varied; hence, land use data were aggregated into six categories corresponding to agriculture, commercial, industrial, open, residential, and other urban.

Rainfall

The Parameter-Elevation Regressions on Independent Slopes Model (PRISM) was employed to generate typical year annual rainfall volumes (Daly and Taylor 1998). This model used rainfall data from 1961 to 1990 in conjunction with elevation information to determine rainfall across the model domain. The rainfall value at the centroid of each watershed was assigned to that watershed. Although average rainfall values were used for estimating runoff volumes, an attempt was made to assess inter-annual precipitation

Table 1. Land use distribution by land use and county for the modeled area (km^2) in the Southern California Bight watersheds.

County	Agriculture	Commercial	Industrial	Open	Residential	Other	Total
Los Angeles	35	306	399	1,798	1,241	20	3,800
Orange	80	183	149	798	564	1	1,775
Riverside	0	66	0	457	355	1	879
San Bernardino	0	1	0	64	10	0	75
San Diego	503	234	173	2,428	834	0	4,172
Santa Barbara	3	94	0	769	81	0	947
Ventura	453	54	103	2,197	198	0	3,005
SCB	1,074	938	824	8,511	3,283	22	14,652

variability. To characterize the model's sensitivity to the inter-annual variability, precipitation data from local gages were used to bracket the "typical" year values (NOAA 1999). The 10th percentile was 47% less than the mean and the 90th, 165% greater.

Runoff Coefficients and Volume

A bounded iterative optimization was used to empirically derive the runoff coefficients from local runoff data. The goal of the optimization was to produce a set of runoff coefficients for each land use type within the SCB with minimal subjectivity. The technique entailed comparing the measured-to-modeled storm volumes and evaluating the residual differences. The sum of the residual differences was set to zero to minimize stormwater load estimation bias. The runoff coefficients were bounded to ensure they were non-negativity and less than unity. Large watersheds had a proportionally large effect on the residual estimation. To minimize the influence of the larger watersheds over the smaller watersheds, the residuals were normalized with respect to drainage area. Bightwide optimized runoff coefficients were applied in conjunction with the watershed land use patterns and typical year rainfall to estimate stormwater runoff for a typical year.

Stream and rainfall data were used to calibrate and validate the stormwater runoff model. Stream data were obtained from local monitoring programs and USGS-gaged sites (RWQCB 1999, U.S. Geological Survey 1999, Gonda 2000). Rain data, at times, were collected at the same site as the stream data; but for the majority of the sites, rain gages from within the watershed were used to assign a rainfall amount to a gage for a specific storm (RWQCB 1999). Data collected by the San Diego, Orange, and Los Angeles county NPDES stormwater monitoring programs were used for calibration (RWQCB 1999). Stormwater volume and rainfall data by storm event were collected from 1993 to 1999, with 280 calibration and 170 verification events from the three counties from 19 and 20 sites, respectively. The data set consisted of those storms that had overall runoff coefficients (rainfall-volume-to runoff-volume ratio) between 0.01 and 1.0. Outliers were removed to ensure that runoff was the dominant forcing function. Events with extreme rainfall, beyond the 10th and 90th percentile, were removed. The resulting data set spanned a range of precipitation events from 2.54 to 56.9 mm.

Water quality

A total of 667 site-events from 45 sites were used to estimate water-quality parameters for model input (RWQCB 1999). The data were collated from San Diego, Los Angeles, and Ventura County municipal stormwater monitoring programs, generated as part of their NPDES permit programs (Figure 1). Sampling consisted of flow-weighted composite samples over the course of an entire storm event. Samples were collected from land use sites that are small, homogeneous land use areas representative of five categories: agriculture (n=18), commercial (n=160), industrial (n=181), open (n=78), and residential (n=230) land uses. The sixth land use category used in the model, other urban, was defined as areas that were a mixture of the major land use categories and included data from all of the urban sources (commercial, industrial, and residential). Hence, we combined the land use sites to derive the concentration for this land use. Since each of the constituent data sets followed a lognormal distribution, we used the geometric mean concentration for estimating average concentrations in each land use category. We also used the 10th and 90th percentile of each data set to estimate the variability associated with water quality.

One factor that hindered our assessment of water quality was the effect of non-detectable (ND) quantities. To overcome the effect of truncated data sets, we set ND = 0 for estimating stormwater loads. Since the true concentration is not known, the effect of ND was assessed by recalculating loading estimates using ND = ½ reporting level and ND = reporting level.

A summary of wet-weather water quality results throughout the SCB was compiled by Schiff (1997). This compilation included estimating mass emission for TSS, nitrate, ammonia, total phosphate, chromium, copper, nickel, lead, and zinc during the 1994/95 wet season to the SCB based upon empirical monitoring data. To validate the modeled wet-weather water quality data generated in this study, we estimated stormwater runoff loadings for the 1994/95 wet season based on recorded rainfall and compared the modeled to the empirical estimates.

Application

Watersheds were grouped into three categories based on their relative degree of urbanization. Less urbanized watersheds contained less than 30% residential, commercial, industrial, and other urban land uses. Similarly, moderately urbanized watersheds contained between 30% and 55% urban land uses and highly urbanized watersheds contained more than 55% urban land uses. The cutpoints for each category were based on a trimodal distribution of cumulative urban land use area among all of the 191 watersheds in the SCB. After modeling mass emissions, the loads from less, moderate, and highly urbanized watersheds were compared relative to their respective areas. To assess the potential contributions from each of the modeled land uses, the flux of constituents from residential, commercial, industrial, agricultural, and open land uses were calculated.

RESULTS

Volume

Two hundred fourteen storms from 19 stations were used to calibrate the model (Figure 2). The simple runoff model was then validated with 172 events at 20 additional sites (Figure 2). The model only slightly overestimated volumes (slope = 1.02) and matched the measured volumes well (R^2 = 0.67) at the validation sites.

An estimated 1.073 x 10^{12} L of stormwater runoff is discharged to the SCB during a typical water year (Table 2). Runoff coefficients and volume varied by land use in the SCB. The lowest runoff coefficients were for largely pervious areas, such as open and agricultural land uses. Conversely, commercial and industrial land uses that are largely impervious had the highest runoff coefficients. Residential land use, which had a median runoff coefficient, discharged the greatest volume of runoff due to its relatively large area (Table 2).

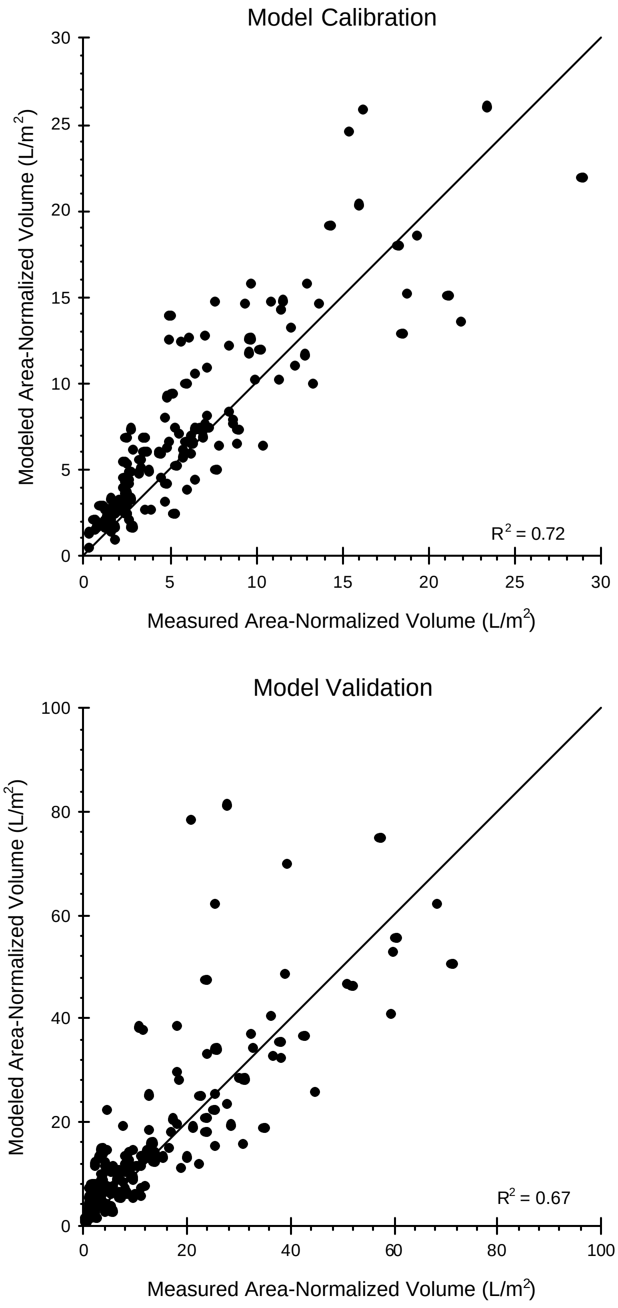

Figure 2. Comparison of modeled and actual volumes discharged during storm events in southern California coastal watersheds for the calibration (19 sites and 214 events) and verification events (20 sites and 172 events).

Table 2. Optimized model runoff coefficients and estimated runoff volumes by land use to the Southern California Bight.

Land Use	Runoff Coefficient	Runoff Volume (L x 10^9)
Agriculture	0.10	40
Commercial	0.61	198
Industrial	0.64	183
Open	0.06	212
Residential	0.39	437
Other Urban	0.41	4
SCB		1,073

Water quality

Compared to the other four land uses, agricultural stormwater runoff had the greatest geometric mean concentrations of all but three of the 15 constituents evaluated (Table 3). Constituent concentrations in agricultural areas were greater by a factor of 1.1 to 81, depending upon the constituent, compared to the constituent concentrations of the second ranked land use. Only the geometric mean concentrations of total phosphate and diazinon in residential land use exceeded concentrations in agricultural land use, but by less than 2%. There were two constituents (chlorpyrifos and total DDT) that were only detected in runoff from agricultural land use and no other. Mercury was not detected in agricultural runoff.

In contrast to agricultural land use, open land use had the lowest geometric mean concentrations for all but two of the 15 constituents evaluated (Table 3). The two constituents were mercury and nickel. Open land uses had the greatest geometric mean concentrations of mercury, although all of the land use concentrations were low (range = 0.04 to 0.07 ug/L), and the second greatest geometric mean concentrations of nickel.

The urbanized categories of residential, commercial, and industrial land uses were relatively similar in geometric mean concentration for most constituents (Table 3). No single urban land use consistently ranked higher than the other for the 15 constituents evaluated. For example, the industrial land use had the greatest geometric mean concentration of the three urban land uses for seven of the constituents, but was nondetectable for five other constituents. Residential land use had the greatest geometric mean concentration for two constituents, but was consistently detected for all but two constituents.

Stormwater Loads

Stormwater runoff from coastal watersheds in the SCB produced substantial quantities of several constituents (Table 4). More than 118,000 MT of suspended solids, 2,300 MT of nitrogenous compounds (nitrate and ammonia), and 147 MT of combined trace metals (cadmium, chromium, copper, lead, nickel, and zinc) are discharged annually. Although discharges of chlorinated hydrocarbons (total DDT) were estimated at over 19 kg in the typical year, most of the samples in the water-quality database were below laboratory reporting levels.

Modeled stormwater loads for suspended solids, ammonia, nitrate, phosphate, chromium, copper, lead, and zinc were compared to empirically estimated loads, using measured flow and water-quality concentrations, to the SCB for water year (WY) 1995 (Schiff 1997). The regionwide rain for WY 1995 was 211% of normal, based upon rainfall records for five stations in San Diego, Los Angeles, and Santa Barbara counties (NOAA 1999). Therefore, the loading model validation used rainfall for WY 1995.

A comparison of the empirical and modeled stormwater loads for a variety of constituents shows remarkable similarity (Figure 3). The modeled stormwater loads were less than a factor of two, on average, different from the empirical load estimates for all constituents evaluated and none more than a factor of 2.1. There was a slight underestimated bias in the modeled results that were attributable to different spatial domains. The empirical data included the areas above the large dams, where this effort did not; thus, we were likely to underestimate the total loadings. However, error or bias was within the large range of water-quality variability either estimated by the model or by empirically derived estimates of stormwater loads.

Model Sensitivity

There was more uncertainty in the modeled estimates of mass emissions associated with water-quality than with rainfall (Figure 4). The maximum uncertainty due to variability in rainfall ranged by a factor of three based on the 10th and 90th percentile of rainfall quantities. However, the difference between the 10th and 90th percentile of water-quality concentrations generated mass emission estimates that differed by a factor of 30, on average, among the constituents with reportable estimates (Table 4). The largest difference was for nickel (580-fold) and the smallest difference was for phosphate (2-fold). The comparison was confounded for four constituents

Table 3. Comparison of water quality analysis for the land use areas in the Southern California Bight watersheds.

Constituent	Land Use	N	N_{ND}	Minimum	10th Percentile	Median	Arithmetic mean	Geometric Mean	90th Percentile	Maximum
Ammonia (mg/L)	Agriculture	15	2	<0.1	0.12	1.5	1.79	1.34	2.96	8.10
	Comercial	224	45	<0.05	0.0	0.27	0.70	0.45	1.34	12.2
	Industrial	274	52	<0.05	0.0	0.28	0.38	0.34	0.8	3.24
	Open	124	83	0.072	0.0	0.0	0.091	0.07	0.20	2.09
	Residential	301	43	<0.05	0.0	0.3	0.53	0.42	1.3	6.19
Cadmimu (ug/L)	Agriculture	15	0	2.4	2.65	4.5	4.66	4.31	7.78	9.50
	Comercial	151	107	<0.05	0.0	0.0	0.41	0.26	1.4	5.2
	Industrial	177	95	<0.1	0.0	0.0	0.69	0.46	2.00	7.0
	Open	72	67	<0.5	0.0	0.0	0.49	0.09	0.0	31.0
	Residential	209	160	<0.1	0.0	0.0	0.32	0.20	1.22	4.4
Chlorpyrifos (ug/L)	Agriculture	15	11	0.11	0.0	0.0	0.38	0.22	1.27	3.30
	Comercial	52	52	<0.05	0.0	0.0	0.0	0.0	0.0	0.0
	Industrial	79	79	<0.05	0.0	0.0	0.0	0.0	0.0	0.0
	Open	27	27	<0.05	0.0	0.0	0.0	0.0	0.0	0.0
	Residential	81	81	<0.05	0.0	0.0	0.0	0.0	0.0	0.0
Chromium (ug/L)	Agriculture	15	0	26.7	42.0	89.0	141	103	240	530
	Comercial	151	92	1.0	0.0	0.0	7.49	1.21	7.8	559
	Industrial	177	79	<0.05	0.0	2.6	6.42	2.49	17.0	86.0
	Open	72	56	1.1	0.0	0.0	7.24	0.81	13.12	200
	Residential	209	135	0.8	0.0	0.0	3.69	1.14	11.2	83.0
Copper (ug/L)	Agriculture	15	0	55.5	63.8	96.0	225	152	547	750
	Comercial	151	7	<0.1	7.8	23.0	32.64	20.8	59.0	320
	Industrial	177	5	4.0	9.16	30.0	46.2	28.4	89.0	990
	Open	72	28	2.0	0.0	6.5	22.9	5.04	50.9	305
	Residential	209	12	4.0	6.08	16.0	25.2	16.2	51.2	210

Table 3 (cont'd). Comparison of water quality analysis for the land use areas in the Southern California Bight

Constituent	Land Use	N	N^{ND}	Minimum	10th Percentile	Median	Arithmetic mean	Geometric Mean	90th Percentile	Maximum
DDT (ug/L)	Agriculture	14	0	0.11	0.15	0.40	0.51	0.46	0.69	2.13
	Commercial	78	78	<0.02	0.0	0.0	0.0	0.0	0.0	0.0
	Industrial	82	78	<0.02	0.0	0.0	0.005	0.0	0.0	0.13
	Open	59	59	<0.1	0.0	0.0	0.0	0.0	0.0	0.0
	Residential	130	128	0.012	0.0	0.0	0.001	0.0	0.0	0.06
Diazinon (ug/L)	Agriculture	15	15	<0.05	0.0	0.0	0.0	0.0	0.0	0.0
	Commercial	52	49	<0.01	0.0	0.0	0.016	0.01	0.0	0.59
	Industrial	81	80	<0.01	0.0	0.0	0.022	0.01	0.0	1.80
	Open	27	27	<0.01	0.0	0.0	0.0	0.0	0.0	0.0
	Residential	82	76	<0.01	0.0	0.0	0.028	0.02	0.0	0.64
Lead (ug/L)	Agriculture	15	0	5.0	16.8	48.5	60.48	43.4	117	161
	Commercial	151	62	<1	0.0	4.0	12.22	3.65	28.0	248
	Industrial	177	49	<1	0.0	7.0	17.4	5.86	45.2	188
	Open	71	70	<0.1	0.0	0.0	2.27	0.07	0.0	161
	Residential	209	88	<1	0.0	5.3	12.9	3.98	37.2	202
Mercury (ug/L)	Agriculture	16	7	<0.1	0.05	0.04	0.12	0.11	0.34	0.60
	Commercial	145	141	<0.5	0.0	0.0	0.041	0.02	0.0	2.85
	Industrial	171	160	0.0192	0.0	0.0	0.28	0.06	0.0	36.0
	Open	71	70	<0.1	0.0	0.0	2.27	0.07	0.0	161
	Residential	196	186	0.0272	0.0	0.0	0.46	0.04	0.0	85
Nickel (ug/L)	Agriculture	15	1	<16	51.8	95.0	109	77.8	178	240
	Commercial	209	23	0.007	0.0	1.0	2.06	1.80	4.97	28
	Industrial	257	19	<0.02	0.18	1.01	1.89	1.29	4.68	15.1
	Open	128	1	0.02	0.44	1.9	2.74	2.04	5.71	12.5
	Residential	269	42	0.06	0.0	1.22	3.30	1.65	7.17	96.3

Table 3 (cont'd). Comparison of water quality analysis for the land use areas in the Southern California.

Constituent	Land Use	N	N^{ND}	Minimum	10th Percentile	Median	Arithmetic mean	Geometric Mean	90th Percentile	Maximum
Nitrate (mg/L)	Agriculture	14	0	1.66	1.84	8.35	10.0	7.31	22.8	25.1
	Commercial	112	49	0.009	0.0	0.0	0.11	0.09	0.28	1.62
	Industrial	133	38	0.005	0.0	0.048	0.066	0.06	0.17	0.41
	Open	62	43	0.021	0.0	0.0	0.02	0.02	0.049	0.29
	Residential	135	50	0.006	0.0	0.037	0.118	0.08	0.15	6.54
Phosphate (mg/L)	Agriculture	8	0	0.32	0.40	0.59	0.57	0.56	0.70	0.75
	Commercial	36	3	0.02	0.15	0.0	0.55	0.49	0.75	3.10
	Industrial	39	6	0.02	0.0	0.40	0.41	0.37	0.8	1.60
	Open	0								
	Residential	33	0	0.16	0.3	0.6	0.60	0.57	1	1.4
Selenium (ug/L)	Agriculture	15	1	0.90	0.94	1.80	1.86	1.62	2.90	5.6
	Commercial	149	134	0.5	0.0	0.0	0.35	0.13	0.1	13.2
	Industrial	175	146	0.5	0.0	0.0	0.59	0.23	1.36	11.9
	Open	72	68	0.5	0.0	0.0	0.35	0.09	0.0	13.9
	Residential	207	184	0.4	0.0	0.0	0.47	0.15	0.5	24.0
Suspended Solids (mg/L)	Agriculture	14	0	625	798	1,191	2,068	1,520	4,871	7,680
	Commercial	134	2	1.0	15.0	58.0	118	56.5	179	2,240
	Industrial	169	2	1	22.0	86.0	174	84.7	329	2,796
	Open	64	2	1.0	3.3	18.0	371	28.8	788	8,728
	Residential	178	3	1.0	13.0	60.0	102	55.2	220	760
Zinc (ug/L)	Agriculture	15	0	3.30	92.8	304	345	223	682	1,150
	Commercial	150	2	25	65.4	157	233	159	437	2,130
	Industrial	177	4	1.2	76.4	218	326	196	580	5,970
	Open	72	49	13	0.0	0.0	45.0	3.19	148	651
	Residential	209	21	0.073	0.058	100	141	69.7	255	1,610

Table 4. Modeled mass emission estimates for stormwater runoff to the Southern California Bight for a typical water year. Model sensitivity was tested by comparing estimated loads with the geometric mean, 90th, and 10th percentile of water quality concentrations.

	Tenth Percentile	Geometric Mean	Ninetieth Percentile[1]
Ammonia (kg)	4,790	406,000	1,160,000
Cadmium (kg)	106	414	1,540
Chlorpyrifos (kg)	0.0	8.78	50.7
Chromium (kg)	1,680	5,500	22,400
Copper (kg)	8,450	23,600	84,000
Total DDT (kg)	5.90	19.3	27.5
Diazinon (kg)	0.0	15	0
Lead (kg)	670	5,420	39,000
Mercury (kg)	0.0	55.7	13.5
Nickel (kg)	2,070	5,040	29,600
Nitrate (kg)	199,000	1,940,000	7,350,000
Phosphate (kg)	261,000	558,000	975,000
Selenium (kg)	37.50	217	668
Suspended Solids (kg)	453,000,000	118,000,000	557,000,000
Zinc (kg)	30,900	108,000	365,000

[1] Constituents with many nondetect samples can result in the geometric mean load being greater than the ninetieth percentile.

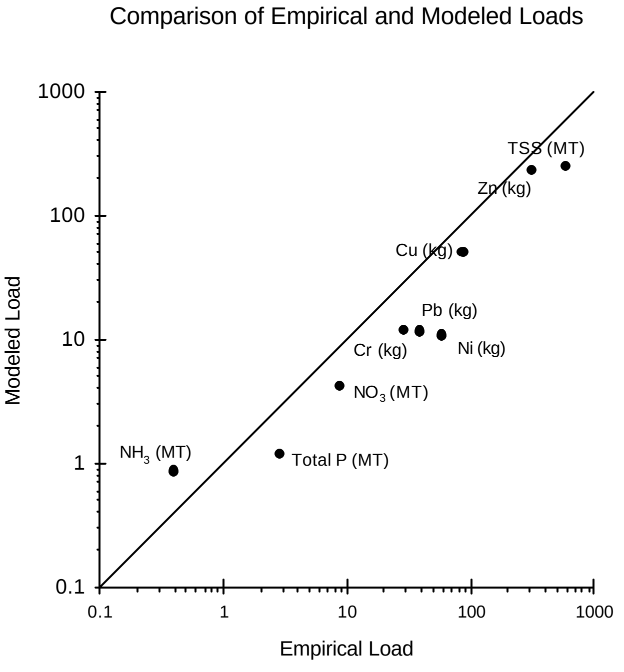

Figure 3. Comparison of empirical and modeled annual stormwater loads to the SCB.

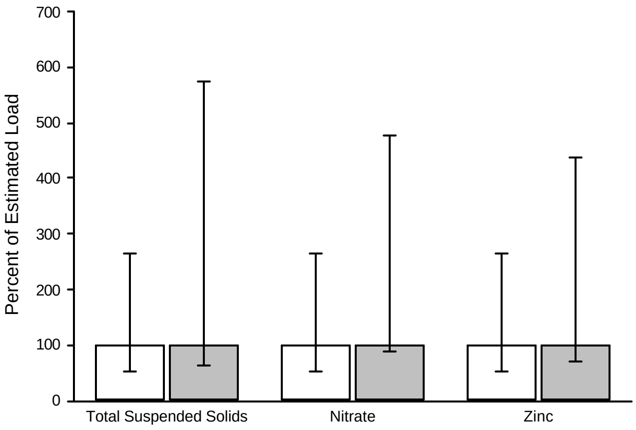

Figure 4. Comparison of variability in water quality concentrations and rainfall on estimated stormwater runoff mass emissions of selected constituents to the Southern California Bight.

because the lower bounds were below detection limits. The loads for chlorpyrifos, diazinon, and mercury were below detection limits when the 10th percentile was utilized. In the case of diazinon, even the 90th percentile was below detection limits, indicating that the geometric mean concentration used in our model was biased by a limited number of samples.

The variable detection limits and number of samples less than detection limit had an impact on the characteristic constituent concentrations. Samples below the detection limit biased the mean concentration and hindered mass emission estimates. The modeled mass emissions were based on non-detect values assigned to zero. We investigated the impact of other non-detect assigning schemes on the total load to the SCB (Table 5). Because data from different agencies were used, detection limits varied widely for some constituents. As one might expect, those constituents with a large number of non-detects resulted in mass emission estimates that vary by an order of magnitude (e.g., chlorpyrifos, total DDT, diazinon, mercury); whereas those constituents with a low proportion of non-detects changed much less (e.g., suspended solids, copper, zinc, nitrate, phosphate).

Assessment

The majority of stormwater runoff mass emissions were generated from highly to moderately urbanized watersheds (Table 6). Highly urbanized and moderately urbanized watersheds represented approximately half of the watershed area and contributed the majority of mass emissions for 10 of 15 constituents. Except for chlorpyrifos, chromium, total DDT, nickel, and suspended solids, highly to moderately urbanized watersheds generated between 56% and 87% of the total stormwater runoff loads to the coastal oceans of the SCB. Highly urbanized watersheds, in particular, generated a disproportionate amount of load relative to its 32% of total watershed area. Between 45% and 56% of the total stormwater load for nutrients (i.e., ammonia, nitrate, and phosphate), 2% 1 and 60% of the trace metals (e.g., copper and zinc) or 9% and 67% pesticides (i.e., chlorpyrifos and diazinon) were generated from highly urbanized land uses.

Differences were observed among watershed types partly because stormwater runoff mass emissions were not generated evenly across land use types (Table 7). Pollutant fluxes are higher from urban or agricultural land uses than fluxes from other land uses. Commercial and industrial land uses had the highest pollutant fluxes among land uses for 4 of the 15 constituents including some trace metals. Agricultural land uses had the greatest fluxes for pesticides such as total DDT and chlorpyrifos. In contrast, open land uses had the lowest fluxes for all constituents.

DISCUSSION

The model developed in this study generated large estimates of stormwater volume and mass emissions for the SCB region. The mass emission estimates predicted in this article exceed the estimates of cumulative mass emissions from traditional point sources within the SCB including publicly owned treatment works (POTWs) (Table 8). Altogether, large POTWs in the SCB discharge more than 1.5 billion liters of treated municipal wastewater and large quantities of many constituents including suspended solids, nutrients, and trace metals to the ocean (Raco-Rands and Steinberger 2001). Stormwater had higher mass emissions than POTWs for eight of the twelve constituents considered. The stormwater mass emissions, placed in this context, represent a pressing environmental management concern in the SCB.

Predicted runoff volumes approximated actual runoff volumes with a relatively high degree of accuracy, largely due to the optimization routine used to derive runoff coefficients. The optimized runoff coefficients were generally lower than are typically used in watershed modeling applications similar to the present study (Table 9). However, the runoff coefficients used in these other modeling efforts have been based on the percent imperviousness while rainfall-runoff data were used as the basis of coefficients in this study. Given the size of the modeled area and land use aggregation, optimizing the runoff coefficients with empirical data provided accurate estimates of the expected runoff coefficients throughout the region, based on verification studies at gages sites.

The large quantity of water-quality data provided a good base from which to calibrate and validate stormwater runoff load estimates. The data collected for southern California for this modeling effort included stormwater volume and water-quality data for 1,766 station events. This data set provided one of the more extensive water-quality data sets in the nation. For example, Smullen *et al.* (1999) recently compiled a comprehensive data set of 816 station-

Table 5. Effects of nondetectable quantities on stormwater load estimates to the Southern California Bight.

	n	ND[1]	NDs as 0	NDs at ½ DL[2]	NDs at DL[2]
Ammonia (kg)	938	225	406,000	425,000	443,000
Cadmium (kg)	624	429	414	860	1,260
Chlorpyrifos (kg)	254	250	8.78	142	207
Chromium (kg)	624	362	5,500	8,340	10,400
Copper (kg)	624	52	23,600	25,500	26,500
Total DDT (kg)	363	343	19.3	68.8	118
Diazinon (kg)	257	247	15	115	160
Lead (kg)	626	259	5,420	8,860	11,000
Mercury (kg)	599	564	55.7	541	1,010
Nickel (kg)	623	351	5,040	8,850	11,400
Nitrate (kg)	877	85	1,940,000	1,960,000	1,970,000
Phosphate (kg)	116	9	558,000	560,000	561,000
Selenium (kg)	618	533	217	2,320	4,130
Suspended Solids (kg)	559	9	118,000,000	119,000,000	120,000,000
Zinc (kg)	623	76	108,000	131,000	140,000

[1] Nondetect.

[2] Detection limit.

Table 6. Stormwater mass emissions to the Southern California Bight characterized by relative amount of urbanization within watersheds.

		Percent of Total Load by Watershed Type		
	Total	Highly Urbanized	Moderately Urbanized	Less Urbanized
Area (km^2)	14,652	32	17	51
Number of Watersheds	191	44	36	111
Volume (L x 10^9)	1,073	46	19	35
Ammonia (kg)	406,000	56.2	20.1	23.8
Cadmium (kg)	414	39.3	16.9	43.8
Chlorpyrifos (kg)	8.78	8.6	13.8	77.6
Chromium (kg)	5,500	21.1	15	63.9
Copper (kg)	23,600	48.4	18.3	33.4
Total DDT (kg)	19.3	11.7	13.8	74.5
Diazinon (kg)	15	66.7	20.8	12.6
Lead (kg)	5,420	46.1	17.8	36.1
Mercury (kg)	55.7	45.6	17.5	36.9
Nickel (kg)	5,040	28.2	15.6	56.1
Nitrate (kg)	1,940,000	44.9	18.4	36.7
Phosphate (kg)	558,000	51.7	19.5	28.7
Selenium (kg)	217	43.9	17.5	38.6
Suspended Solids (kg)	118,000,000	33.4	16.5	50.1
Zinc (kg)	108,000	59.9	19.7	20.3

Table 7. Flux of stormwater runoff constituents (kg/km^2) by land use in the Southern California Bight.

	Agriculture	Commercial	Industrial	Open	Residential	Other Urban	SCB-wide
Ammonia	49.9	94.1	74.5	1.83	56.5	65.8	27.7
Cadmium	0.16	0.054	0.1	0.0023	0.027	0.049	0.028
Chlorpyrifos	0.008	-	-	-	-	-	0.0006
Chromium	3.85	0.25	0.55	0.02	0.15	0.25	0.38
Copper	5.64	4.39	6.3	0.13	2.15	3.45	1.61
Total DDT	0.017	-	0.001		0.00007	0.0002	0.0013
Diazinon	-	0.0027	0.0028	-	0.0031	0.0028	0.001
Lead	1.61	0.77	1.3	0.02	0.53	0.73	0.37
Mercury	0.004	0.005	0.014	0.002	0.006	0.007	0.004
Nickel	2.89	0.4	0.86	0.024	0.2	0.37	0.34
Nitrate	271	275	287	50.8	219	234	132
Phosphate	20.9	103	83.1	14	76.1	77.4	38.1
Selenium	0.06	0.027	0.052	0.0022	0.02	0.028	0.015
Suspended Solids	56,400	11,900	18,800	717	7,340	10,600	8,050
Zinc	8.28	33.6	43.5	0.079	9.27	20.4	7.37

Table 8. Comparison of mass emissions from publicly owned treatment works (POTWs) and stormwater runoff to the Southern California Bight.

Constituent		Stormwater	POTW[1]
Volume	($Lx10^9$)	1,073	1,572
Ammonia-N	(mt)	406,000	42,016,000
Cadmium	(mt)	410	400
Chromium	(mt)	5,500	4,200
Copper	(mt)	23,600	59,000
Lead	(mt)	5,420	800
Nickel	(mt)	5,000	35,000
Nitrate	(mt)	1,940,000	154,000
Phosphate	(mt)	558,000	1,733,000
Selenium	(mt)	220	8,400
Suspended Solids	(mt)	118,000,000	75,105,000
Zinc	(mt)	108,000	82,000
Total DDT	(kg)	19	2.1

[1] (Raco-Rands and Steinberger 2001)

Table 9. Comparison of runoff coefficients from this study with other studies.

	Modeled Coefficient (this study)	Wrong *et al.* (1997)	Escobar (1999)	Stephenson (1981)
Agriculture	0.10	-	-	0.30
Commercial	0.61	0.74	0.48 – 0.90	0.50 – 0.90
Industrial	0.64	0.74	0.44 – 0.90	0.50 – 0.90
Open	0.06	0.10	0.11 – 0.22	0.10 – 0.40
Residential	0.39	0.39 – 0.58	0.18 – 0.83	0.30 – 0.70

events from over 30 NPDES programs nationwide. The level of effort expended in the SCB is of similar magnitude as the Nationwide Urban Runoff Program, which sampled approximately 2,000 station events at 28 cities (U.S. EPA 1983).

Although the regionwide water-quality data set appears extensive, it was limited in three ways. First, the stormwater sampling strategy for each county concentrated on urbanized areas and the data set was sparse for some land use types. Specifically, the agriculture category was not represented well, with only two agricultural land use sites. These data were used to extrapolate the runoff characteristics of agricultural areas in the region, a practice that may not be as thoroughly representative as results from other land uses. The second limitation of the water-quality data set was lack of samples for specific constituents. For example, some organophosphate pesticides (i.e., diazinon and chlorpyrifos) were sampled less frequently than other constituents. The third factor was reduced sample size, particularly of important constituents, which limited our ability to model representative concentrations. Loading estimates to the SCB were affected by treatment of values below detection limits. Estimates varied by up to several orders of magnitude depending on the number of values below the detection limit. Obtaining data with sufficient resolution was critical to reduce this variability, especially with trace constituents (e.g., total DDT and mercury).

The model provided an estimate of the mass loading to the SCB during a typical year. We saw that the model was sensitive to rainfall, but moreso to water-quality concentrations. Constituent concentrations from a given land use will vary from site to site and storm to storm. This variability is magnified when the area of interest is expanded from single land use areas to watersheds because of runoff behavior and complexity. Our assumptions were based on investigating long-term loading to the SCB, but understanding inter-storm and intra-site variability is critical to estimate loads on a shorter time scale.

Although model predictions are robust (as demonstrated by the validation data, Figure 2) all models have limitations. Our simple runoff model made many assumptions, the largest of which was that pollutants near the coast are transported with equal efficiency as those that originate in headwater regions. We know this is not the case, particularly for those constituents that can transform or degrade, such as nutrients and bacteria. To overcome these assumptions, more complex models such as HSPF (Bicknell, Imhoff *et al.* 1997), SWMM (Huber and Dickinson 1988), or SPARROW (Smith, Schwarz *et al.* 1997) are required to incorporate additional hydraulic, hydrodynamic, and water-quality processes.

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