Review of Existing Stormwater Monitoring Programs for Estimating Bight-wide Mass Emissions from Urban Runoff

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ABSTRACT

Urban runoff is perceived as a large source of pollutant inputs to the ocean, but no mass emission monitoring programs have been established to assess this discharge. Recently, however, National Pollutant Discharge Elimination System permits for urban runoff discharges were issued to stormwater management agencies on a regional (county-wide) basis and the 1994-95 water year represents the first period in which urban runoff water quality measurements have been monitored bight-wide. The goal of this study was to use the data generated by these monitoring programs to estimate mass emissions of pollutants to the Southern California Bight from urban runoff.

After documenting the sampling design of each stormwater monitoring program, then collating information on rainfall, watershed area, runoff volume, and water quality measurements, we estimated the mass emissions of total suspended solids, nutrients (ammonia, nitrate, phosphorous), and five trace metals (chromium, copper, nickel, lead, zinc). Although the mass emissions of these constituents appeared substantial relative to other sources, there was tremendous uncertainty in the load estimates. Less than 5% of the watershed areas and less than 2% of the annual runoff volumes were actually monitored during 1994-95 water year. Extrapolation of water quality data to these unmonitored channels and flows, which is necessary to develop bight-wide emission estimates, are hampered by the tremendous variability in contaminant concentrations among the different watersheds and storm events. This variability in water quality measurements from urban runoff are not well understood. This lack of understanding adds to our uncertainty in the load estimates we provide.

INTRODUCTION

Rivers in southern California are amongst the most extensively modified channels in the world (Brownlie and Taylor 1981). These storm drain systems, which ultimately discharge directly to the ocean, were designed to remove stormwater from streets and low-lying areas as efficiently as possible, thus reducing flooding and minimizing property damage. Most of the modification to these channels occurred prior to an era of interest or knowledge about urban runoff water quality. As a result, accumulated debris, pollutants, and pathogens from the largest metropolitan centers on the west coast are discharged along with this urban runoff. Moreover, many urban runoff discharges are augmented by inland municipal/industrial treated wastewater discharges, potentially contaminated groundwater discharges, and at times, inputs from illegal discharges and illicit connections. There is little in the way of retention and virtually no treatment of runoff from southern California urbanized watersheds. Only relatively recently has concern regarding water quality of these urban runoff discharges been examined (SMBRP 1996, Schiff and Stevenson 1996, Bay *et al.* 1996, Suffet *et al.* 1993, Gold *et al.* 1992, SCCWRP 1980).

Although urban runoff is currently perceived as a potentially large source of contaminants to our near coastal environment (Eganhouse and Kaplan 1987, RWQCB-LA 1988, USEPA 1995), there has been little monitoring for estimating contaminant mass emissions to the Southern California Bight (SCB). One reason for the lack of quantified loadings is because sampling and characterizing runoff discharges is extremely difficult. Unlike many other point sources of pollutants to the ocean, such as treated municipal or industrial wastewaters, the ubiquitous nature of urban runoff prohibits characterization from a single location or at infrequent intervals. The unpredictable rainfall in southern California further complicates runoff monitoring since the resulting flows are discontinuous and highly variable. Historically, most runoff measurements for estimating contaminant mass loadings to the ocean have been the result of special studies (SCCWRP 1973; 1990; 1992). Re-authorization of the Clean Water Act in 1987 and associated litigation have now required regulatory permitting of stormwater discharges. Most of this regulatory burden, both technical and fiscal, has been tasked to the stormwater management agencies, whose mission has traditionally been building and maintaining our flood control channels.

The State of California, through its Regional Water Quality Control Boards, issued four region-wide National Pollutant Discharge Elimination System (NPDES) Permits between 1990 and 1993 for urban stormwater discharges to the SCB (Table 1; Figure 1). Each permit has many co-permittees including counties, incorporated cities within the counties, and special districts (e.g., Port District). The principal permittees are the Ventura County Flood Control District (Ventura Co.) for the Ventura County Region-wide Permit, Los Angeles County Department of Public Works (LA Co.) for the Los Angeles County Region-wide Permit, Orange County Flood Control District (Orange Co.) for the Orange County Region-wide Permit, and the City of San Diego (San Diego Co.) for the San Diego Region-wide Permit. All permittees are mandated to create a stormwater management plan (SWMP), part of which is water quality monitoring. Although monitoring programs are mandated by each NPDES Permit, they have not been standardized within the SCB.

TABLE 1. Summary of municipal urban runoff NPDES permits for the coastal Southern California Bight.

Principal Permittee	Number of Co-Permittees	NPDES No. (Regulatory Agency)	Major Watercourses Listed in Permit
Ventura County Flood Control District	11 Municipalities	Order No. 94-082 NPDES No. CAS063339 (Los Angeles Regional Water Quality Control Board)	1. Ventura Rivera 2. Santa Clara River (part) 3. Calleguas Creek 4. Malibu Creek (part)
Los Angeles County Department of Public Works	85 Municipalities	Order No. 96-054 NPDES No. CAS614001 (Los Angeles Regional Water Quality Control Board)	2. Santa Clara River (part) 4. Malibu Creek (part) 5. Ballona Creek 6. Dominguez Channel 7. Los Angeles River 8. San Gabriel River
Orange County Flood Control District	26 Muncipalities	Order No. 96-31 NPDES No. CAS618030 (Santa Ana Regional Water Quality Control Board)	9. Santa Ana River (part) 10. Silverado/Santiago Creek 11. San Diego Creek
City of San Diego	18 Municipalities and Port District	Order No. 90-42 NPDES No. CAS0108758 (San Diego Regional Water Quality Control Board)	12. Santa Margarita River 13. San Luis Rey River 14. Escondido River 15. San Dieguito River 16. Los Penasquitos Creek 17. San Diego River 18. Sweetwater River 19. Otay River 20. Tijuana River

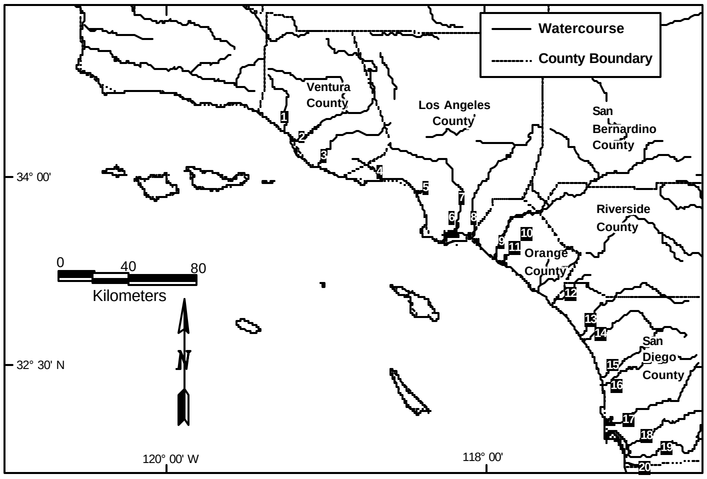

FIGURE 1. Map of major watercourses named in the four County-wide NPDES Municipal Stormwater Permits which discharge to the Southern California Bight. (See Table 1 for the names of individual rivers and creeks.)

The objectives of this study were three-fold. For each of the urban runoff water quality monitoring programs in the SCB during the 1994-95 water year, we attempted to:

1) Document the sampling designs of each water quality monitoring program;

2) Collate rainfall, watershed area, runoff volume, and water quality information from each of the monitoring programs and use this information to estimate bightwide mass emissions; and

3) Evaluate our ability to calculate mass emission estimates based upon the current monitoring programs.

MATERIALS AND METHODS

Each stormwater management agency's Annual Discharge Monitoring Report (ADMR) was reviewed to document sampling designs, collate data for water quality and flow measurements, and evaluate monitoring programs for estimating bight-wide mass emissions from urban runoff (VCFCD 1995; LACDPW 1996; OCEMA 1996; KLI 1995). The most recent year for which an ADMR was available for all permittees was the 1994-95 water year (October 1994 through September 1995). Each ADMR was obtained from the RWQCB files or from the permittee.

For the purposes of this article, several assumptions were required. First, only watersheds listed in the NPDES permits were considered, including areas beyond the urban limit line. Where watersheds were split between permits (i.e., Santa Clara, Santa Ana, and Santa Margarita Rivers), the region for which the discharge entered the ocean was chosen as the area encompassed in permitted discharge. Significant impoundments exist on most rivers of the SCB, but no attempt was made to remove upstream portions of watersheds from the estimated discharge area. However, only flows downstream of dams were considered for discharges to the ocean. No runoff factors were used to estimate unmonitored flows; only gaged flows to the SCB were utilized. It was assumed that flow and analytical chemistry measurements were conducted (and recorded) without error.

Documentation of Existing Monitoring Programs

Documentation of the existing monitoring programs focused on three areas: (1) station selection; (2) storm sampling criteria; and (3) target analytes and detection limits. For station selection, the general strategy for site selection, the number of sites sampled, and the watershed area encompassed by that site were identified. For storm sampling criteria, the minimum storm size, total number of storms sampled, and sampling methodology were identified.

Estimation of Runoff Mass Emissions By Collating Monitoring Data

A simplistic, watershed-based approach was used to calculate mass emissions of contaminants from urban runoff to the SCB in 1994-95 illustrated by the following equation (1):

$$(1) \qquad L_{annual} = \sum_{i=1}^{n} (EMC_{median} * Volume_i)$$

Where,

L_{annual} = Annual pollutant load;

i = Watershed listed in the NPDES permit;

Volume = Annual volume of watershed$_i$; and

EMC_{median} = Bightwide median event mean concentration.

Annual runoff volume for each watershed was obtained from either the ADMRs, the United States Geological Survey (USGS 1995), LA Co. - Engineering Section, Orange Co. Environmental Management Agency, San Diego Co. Flood Control District, or the International Boundary Water Commission (IBWC). Rainfall data, summarized from the National Weather Service (Nationwide Climatic Data Center, Ashville, NC), was used to complement flow data, demonstrate part of the variability responsible in flow among regions, and assess the relative discharges this water year compared to "normal" years as determined from long-term rainfall records. Additional information collated from these sources included 15 min. average flow during storm events and total volume discharged during storm events to assess volumes representatively sampled versus discharged.

Bight-wide median event mean concentrations (EMC) were calculated from the midpoint in the distribution of all the water quality data for a particular constituent reported in the 1994-95 ADMRs. The EMC is equivalent to the concentration designated as representative of each storm event by each monitoring agency. It is defined as the sum of all volume-weighted concentrations divided by the total storm volume (USEPA 1983). The only water quality data we collated for median EMC calculations were channel sites where an entire watershed was sampled. No sub-watershed, land use sites were used to calculate median EMCs. We also compared water quality results for the different region-wide permits by calculating 1994-95 median EMCs for individual SCB watersheds where the data were available.

Our watershed-based approach required pooling data to estimate water quality for channels not sampled. Because we had to extrapolate concentrations to unsampled watersheds, which adds some uncertainty to our estimates of mass emissions, we also calculated mass emissions based upon the 10th and 90th percentile concentrations observed among watersheds. Our intention in the calculations was to capture the uncertainty in the extrapolations we have made.

Evaluation of Monitoring Data for Calculating Bightwide Mass Emissions from Runoff

The ability to calculate bightwide mass emissions from urban runoff based upon the monitoring data from 1994-95 was judged by two factors: (1) an assessment of monitoring coverage; and (2) the commonality of methods among monitoring programs. Monitoring coverage was assessed in terms of the percent of the area monitored and the percent of runoff volume representatively sampled. Commonality among programs included such factors as numbers and types of storms captured, sampling methodology and frequency, and comparability of analytical chemistry.

RESULTS

Documentation of Existing Monitoring Programs

Two general types of monitoring sites are currently being used by the stormwater management agencies in the SCB. The first type of monitoring site samples an entire watershed composed of large areas (10^1 to 10^3 km^2) and a diverse mix of land use types by sampling water quality at or near the end of a river or creek. The goal of this monitoring design is to characterize the cumulative discharges from all sources within the entire watershed. We refer to these as “channel sites.” The second type of monitoring site samples sub-watersheds composed of small areas (10^{-2} to 10^0 km^2) and a single homogeneous land use. The goal of this monitoring design is to characterize particular runoff sources (e.g. residential, commercial, industrial, etc.). We refer to these as “land use sites.”

Fifteen of the 36 sites monitored by stormwater management agencies in 1994-95 were channel sites (Table 2). Orange Co. sampled channel sites exclusively (eight total, including the only unlined earthen channels). In contrast, Ventura Co. sampled only land use sites (seven total, including the only agricultural land use monitored). San Diego Co. sampled more sites in 1994-95 than any other stormwater management agency in the SCB (nine land use and three channel sites).

TABLE 2. Number and type of stations monitored by NPDES municipal stormwater agencies.

	Ventura County	Los Angeles County	Orange County	San Diego County
Land Use Sites				
Residential	3	2	-	3
Commercial	1	1	-	3
Industrial	2	1	-	3
Open	-	1	-	-
Agriculture	1	-	-	-
Channel Sites	-	4	8	3
(watersheds)	-	(2)	(2)	(2)

All of the stormwater monitoring programs in the SCB used storm mobilization criteria to trigger crews into action (Table 3). The first criterion was minimum storm size, as estimated from predicted rainfall quantities, which ranged from 0.10 to 0.25 inches among monitoring programs. The second criterion was antecedent dry period between storms, which ranged from three to four days among monitoring programs. Only the San Diego Co. NPDES permit specified the individual storms that must be captured, including the first two significant storms of the season and one late season storm (after February 1). Except for Los Angeles Co., monitoring programs in the SCB were required to sample a minimum of three storms per site each year; Los Angeles Co. was required to sample five storms per site each year.

Two types of samples were collected by the monitoring agencies (Table 3). The first type was a grab sample consisting of a bottle or bucket lowered into the channel or manhole. The second type was a composite sample, typically collected using a peristaltic pump with an intake strainer mounted in the bottom of channels or pipes. Composite samples, however, were weighted differently among agencies (Table 3). Ventura Co., Los Angeles Co., and San Diego Co. used a single composite sample per event weighted by storm flow (e.g., sampling every set volume interval). In contrast, Orange Co. measured two to three composite samples per event, each weighted by time (e.g. every hour, every 15 minutes, etc.). Although sampling frequency within a composite can vary as a result of storm duration or volume, automated samplers were programmed differently among monitoring agencies. The resulting sampling frequencies varied from four to over 40 per storm event (Table 3).

TABLE 3. 1994-95 storm mobilization criteria and storm capture parameters for management agencies which monitor urban runoff in the SCB.

	Ventura County	Los Angeles County	Orange County	San Diego County
Storm Mobilization Criteria				
Antecedent rainfall	72 hr	72 hr	96 hr	72 hr
Predicted rainfall quantity	0.10 in	0.25 in	0.10 in	0.10 in
Min. No. Storms/Station/Year	3	5	3	3
No. Samples/storm				
Grab samples	1	1	1	1
Composite samples	1	1	2 - 3	1
No. samples per composite	12-40+	4+	4-24+	12-40+
Composite weighting	Flow	Flow	Time	Flow
Min. Flow Capture Criteria	Yes	No	Yes	Yes
Storm capture	80%	-	75%	80%
Storm end trigger	120% of base flow	-	96 hr from start of flow	120% of base flow

Minimum flow requirements were defined by each monitoring agency to identify when to end sampling and evaluate the acceptability of a storm event (Table 3). Typically two trigger levels were used to conclude sampling. First, peak flows needed to recede to 120%, or less, of baseline pre-storm flow. Alternatively, the time since rainfall concluded needed to exceed a minimum interval (typically 96 hr.). Three of the four agencies reported the storm capture percentage which is equivalent to the volume representatively sampled compared to the total storm volume discharged. For those agencies that reported storm capture criteria, most events were greater than 75%.

Each of the stormwater management agencies analyzed a variety of constituents for their water quality assessments of urban runoff including general characteristics, inorganic analytes such as trace metals, and organic constituents such as chlorinated and petroleum hydrocarbons, toxicity tests with invertebrates or vertebrates, and fecal indicator bacteria (Table 4). Since not all constituents are measured during every storm or at every station, only those analytes and detection limits routinely listed in their respective ADMRs were reported. Thirteen analytes were measured in common between the four region-wide stormwater permits in the SCB. Some individual permittees, however, measured as many as 183 analytes for a given sample.

Collating Monitoring Data and Estimation of Mass Emissions

Rainfall. Annual rainfall varied from 44 to 73 cm throughout the coastal SCB (Figure 2). As expected, precipitation patterns across the SCB were highest in the north and steadily declined moving south. Oxnard received 66% more rainfall compared to San Diego. In 1994-95, the annual rainfall was approximately double the long-term average. Although precipitation was recorded between 9 and 10 months of the year, the majority of rain fell in the months of January and March. These two months represented 69 to 80% of the rainfall for the entire year, depending upon the gage site.

Watershed Area and Runoff Volume

The total watershed area of the rivers and creeks named in Southern California NPDES stormwater permits was roughly 26,000 km^2 (Table 5). Approximately 90% of this area was gaged for urban runoff flows by a variety of agencies; 2.9 x 10^{12} L were measured during the 1994-95 water year (Table 5). Three rivers discharged over half of the gaged volume to the SCB. Annual discharges from the Los Angeles River, Santa Clara River, and Santa Ana River cumulatively exceeded 1.7 x 10^{12} L, but their watersheds represented only 41% of the SCB area.

When examined on a region-by-region basis, the San Diego Co. NPDES permit (10,800 km^2) encompassed nearly double the watershed area of the other three permits (4,900 to 5,500 km^2). Annual discharge volume in the Los Angeles region (1.13 x 10^{12} L), however, was between 175% and 230% greater than the other three regions (0.49 to 0.65 x 10^{12} L).

Water Quality

Suspended solids, nutrients (nitrogen, ammonia, and phosphorous), and five trace metals (Cr, Cu, Pb, Ni, and Zn) were consistently analyzed and reported among the various NPDES stormwater monitoring programs of the SCB that sampled channel sites (Table 6). Other water quality parameters were measured frequently by individual agencies, but not consistently among all permits or at all sites within a permit. Organic constituents such as PAHs,

TABLE 4. Target analytes and detection limits for NPDES stormwater monitoring programs in the SCB.

		Ventura County	Los Angeles County	Orange County	San Diego County
TSS	mg/l	9[a]	1	5	4
TDS	mg/l	24[a]	5	-	10
Turbidity	ntu	-	0.1	0.5	0.5
Hardness	mg/l	9[a]	5	22[a]	1
Ammonia-N	mg/l	0.1	0.1	0.1	0.1
Nitrite-N	mg/l	0.01	0.03	-	0.05
Nitrate-N	mg/l	0.08	0.03	0.2	0.05
TKN-N	mg/l	0.4	0.03	0.5	1
Total Phos	mg/l	0.1	0.05	0.1	0.05
Diss Phos	mg/l	0.1	0.05	-	0.05
BOD	mg/l	4	1.0	-	3
COD	mg/l	20	50	-	1
TOC	mg/l	2	1	-	-
Oil & Grease	mg/l	1	1	-	0.5
TRPH	mg/l	-	1	-	0.5
Antimony	µg/l	5	10[b]	-	1[b]
Arsenic	µg/l	1[b]	10[b]	-	5[b]
Beryllium	µg/l	0.5	5[b]	-	1[b]
Cadmium	µg/l	0.1[b]	10[b]	1-20	0.2[b]
Chromium	µg/l	0.5[b]	10[b]	6-40	1[b]
Copper	µg/l	4[b]	10[b]	20-30	5[b]
Iron	µg/l	-	100[b]	-	-
Lead	µg/l	1[b]	10[b]	2	1[b]
Mercury	µg/l	0.5[b]	1[b]	-	0.5[b]
Nickel	µg/l	1[b]	10[b]	3-40	5[b]
Selenium	µg/l	0.4[b]	5[b]	-	0.5[b]
Silver	µg/l	0.1[b]	10[b]	1-10	0.2[b]
Thallium	µg/l	1	10[b]	-	1[b]
Zinc	µg/l	3[b]	50[b]	10	5[b]
PAH	µg/l		0.5-3.0	-	1.5-44
Total DDT	µg/l		0.1	-	2-6
Total PCB	µg/l		0.5	-	10-36
Toxicity	% Effluent				
Cerodaphnia dubia		0.1	-	-	0.1
Pimephales promelas		-	-	-	0.1
Total coliforms	mpn/100 ml	2	20	-	2
Fecal coliforms	mpn/100 ml	2	20	-	2
Fecal streptococcus	mpn/100 ml	2	20	-	2
Enterococcus	mpn/100 ml	-	20	-	-

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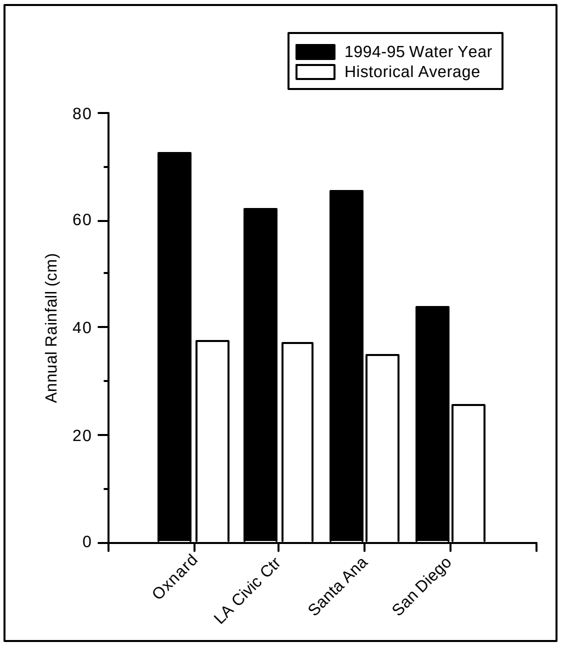
[a] No sample undetected.
[b] Dissolved metals also measured.
-=Not analyzed.

DDTs, and PCBs were frequently measured, but virtually all measurements for these compounds were below reported detection limits.

FIGURE 2. Annual rainfall at four locations in the Southern California Bight. (Data from the National Climatic Data Center, Ashville, NC)



No single region had all the highest or all the lowest median EMCs at channel sampling sites during 1994-95 (Table 6). The range of EMCs between regions differed by a factor of 2 to 20 among the general constituents and by a factor of 1 to 15 among the trace metals. This magnitude of variability was also observed between sites within a single region (Table 6). For example, the range of median EMCs among SCB regional permits for suspended solids was 175 to 330 mg/L. The range of EMCs between different monitoring sites within the San Diego region was 148 to 485 mg/L while the EMCs from various sites within the Orange County region ranged from 41 to 2,148 mg/L.

Mass Emission Estimates from Urban Runoff to the SCB.

Bight-wide median EMCs and mass emissions from urban runoff were estimated for the 1994-95 water year (Table 7). The total load of suspended solids was estimated to be 598 x 10^3 metric tons (mt). Using the 10th and 90th percentile of the distribution of EMCs within the SCB, low and high load estimates varied from 199 x 10^3 mt to 2,594 x 10^3 mt. The combined load of five trace metals (chromium, copper, lead, nickel, and zinc) was estimated to be 531 mt, although estimates varied from 236 to 1,807 mt.

Evaluation of Monitoring Data for Calculating Bightwide Mass Emissions from Runoff

Calculating mass emissions from urban runoff to the SCB from the current monitoring data was constrained by missing data from unmonitored watersheds (i.e., unsampled channels) and unmonitored flows (i.e., unsampled storms) (Figure 3). The watershed area sampled by stormwater monitoring agencies during the 1994-95 water year was approximately 1,162 km^2 or 4.5% of the entire area discharging to the SCB which are listed in NPDES permits. Likewise, a very low percentage of the annual discharge volume was monitored. Approximately 0.06 x 10^{12} L was representatively sampled for analysis during the 1994-95 water year, less than 2% of the annual volume. Of the SCB's largest watersheds (Los Angeles, San Gabriel, and Santa Clara Rivers), only 0.5 km^2 and 0.15 x 10^9 L was sampled.

Although the four stormwater monitoring programs targeted similar numbers, sizes, and types of storms, each sampled its storms differently. The data set used for this study consisted of grab, single and multiple-weighted composite samples. Furthermore, some agencies used time-weighted and others flow-weighted composites. Finally the sampling frequency within composites varied from 4 to 40+. Not all agencies used storm capture criteria, but those that did met expectations of ≥ 75% or more of the storm volume representatively sampled.

Each of the stormwater monitoring agencies analyzed at least nine constituents in common for which bight-wide mass emissions could be calculated (TSS, nutrients, and five trace metals). One agency measured as many as 183 constituents per sample. The methods cited in each of the ADMRs were comparable to Environmental Protection Agency (EPA) protocols. However, many organic compounds were non-detectable using these methods. Detection limits for trace metals were generally not problematic (i.e., usually detected), except for those agencies attempting to measure dissolved fractions.

DISCUSSION

Two approaches are generally used to calculate mass emissions from runoff to the SCB. There is a watershed-based approach which is empirical; concentrations and volumes are measured directly at the terminus of a channel prior to entering the receiving waters. The other approach employs a land use model which estimates runoff volumes based upon quantity of rainfall (from rain gages), watershed area, and coefficients of runoff (based upon imperviouseness). Typically, runoff models also rely upon representative land use sites for water quality data. The watershed-based approach was chosen for this study because channel sites required fewer assumptions to estimate mass emissions to receiving waters. A land use

TABLE 5. Watershed characteristics of creeks and rivers listed in NPDES stormwater permits of southern California, 1994-1995.

		Watershed Characteristics	
Channel	Gaging Agency @ Location	Size (km^2)	Volume (L x 10^9)
Ventura River	USGS @ Casitas Pass Rd	487	53
Santa Clara River	USGS @ Montalvo Rd	4,219	496
Calleguas Creek	USGS @ State Hospital	837	100
Malibu Creek	LACDPW @ Piuma Rd	284	malfnx gage
Ballona Creek	LACDPW @ Beloit Ave	338	92
Other SMB Monitored Watersheds	LACDPW @ 7 subwatersheds	451	not gaged
Dominquez Channel	LACDPW	41	not gaged
Los Angeles River	USGS @ Willow St	2,155	882
San Gabriel River	USGS @ Spring St [a]	1,663	155
Santa Ana River	USGS @ Fifth St	4,406	346
San Diego Creek	USGS @ Campus	288	76
Other OC Monitored Watersheds	OCEMA @ 2 subwatersheds	193	69
Santa Margarita River	USGS @ Basilone Rd	1,873	164
San Luis Rey River	USGS @ Interstate 5	1,443	167
Escondido Creek	SDCFCD	198	not gaged
San Dieguito River	SDCFCD	116	not gaged
Los Penasquitos Creek	USGS @ Cypress Creek	109	27
San Diego River	USGS @ Fashion Valley Rd	1,119	75
Sweetwater River	USGS above reservoir	139	not gaged
Otay River	USGS above reservoir	236	not gaged
Tijuana River	IBWC @ Dairy Mart Rd	4,483	217
Other San Diego Monitored Watersheds	City of SD/SDCFCD	1,062	not gaged
Total		26,140	2,919

USGS = United States Geological Survey.
VCFCD = Ventura County Flood Control District.
LACDPW = Los Angeles County Department of Public Works.
OCEMA = Orange County Environmental Management Agency.
SDCFCD = San Diego County Flood Control District.
IBWC = International Boundary Water Commission.
[a]=Includes Coyote Creek and San Gabriel River combined.

model was not applied because the ADMRs we reviewed lacked the water quality data for some land uses that may contribute substantial quantities of constituents to the SCB. Moreover, we lacked the necessary data to sufficiently calibrate and validate a land use model which would require a combination of both land use and channel site monitoring.

Although the watershed-based approach requires fewer assumptions than the land use model, it was not completely empirical. The watershed-based approach is most effective on a channel-by-channel and storm-by-storm basis. However, the stormwater monitoring agencies are not mandated by the RWQCB to monitor every channel or every storm. As a result, the data set was incomplete and a number of assumptions were required that introduced considerable uncertainty in the quality of our mass emissions estimates. First, it was necessary to assume that water quality measurements in monitored channels were equivalent to those from unmonitored channels. Based upon water quality results from monitored channels, 1994-95 median EMCs for channels within a county and between counties fluctuated widely, often ranging an order of magnitude or more for most constituents. Studies by SCCWRP (1992) also demonstrated tremendous variability among watersheds. For example, suspended solids flow-weighted mean concentrations ranged from 283 to 4,313 mg/L among the eight largest rivers and creeks in southern California during 1986-88. In 1994-95, only one of these eight channels was actually monitored by the stormwater management agencies. Since the corresponding data were not available from all channels, we are unable to assess the bias associated with our extrapolation to unmonitored watersheds.

A second assumption we used was that the temporal periods sampled within a watershed were representative of other periods which were not sampled. Assumptions based upon extrapolations to unsampled storms introduces uncertainty because of flow-related variability. Studies on the Los Angeles River and other channels of the SCB observed significant correlations between flow and pollutant concentrations (SCCWRP 1990). Consequently, mass emission estimates for specific runoff events differ between large and small storms as a result of changing constituent concentrations as well as discharge volumes. Therefore, missing or capturing significant events can result in potential bias depending upon the magnitude of the storm size. Capturing the largest storm of the year may result in the largest EMCs and will likely overestimate the unsampled, but smaller-sized storms. Alternatively,

TABLE 6. Regional event mean concentrations (EMC) for channel sites monitored in the SCB during the 1994-95 water year.

	Median EMC for All Sites[a]			Median EMC per Site[b]	
	Los Angeles County	Orange County	San Diego County	Orange County	San Diego County
General Constituents, mg/l					
TSS	220	192	330	41 - 2,148	135 - 360
TDS	260	-	260		242 - 570
Ammonia-N	0.3	0.2	0.4	0.1 - 0.6	0.4 - 0.7
Nitrate-N	1.5	6.0	0.85	3.3 - 29.0	0.80 - 1.1
TKN-N	-	2.9	3.7	1.2 - 4.7	1.4 - 3.9
Total Phos	0.3	1.5	0.7	1.1 - 6.6	0.5 - 1.1
Diss Phos	-	-	0.4		0.3 - 0.4
BOD	15.8	-	21		20 - 22
COD	-	-	105		96 - 190
Oil & Grease	1.0	-	1.6		1.2 - 2.0
Trace Elements, µg/l					
Cadmium	nd	0.6	0.8	0.5 - 3.7	0.3 - 1.3
Chromium	<10	5.0	3.5	5 - 71	2.8 - 5.6
Copper	25	32	25	27 - 80	11 - 38
Lead	10	14	44	7 - 47	16 - 120
Mercury	nd	-	nd		nd
Nickel	<10	20	7.6	20 - 40	6 - 11
Silver	nd	0.5	nd	0.4 - 0.9	nd
Zinc	79	120	180	69 - 220	61 - 250
Trace Organics, µg/l					
Total PAH	nd	-	nd		nd
Total DDT	nd	-	nd		nd
Total PCB	nd	-	nd		nd
Acute/Chronic Tox, NOEC % Effleunt					
Ceriodaphnia dubia	-	-	25/25		13-25/13-25
Pimephales promelas	-	-	100/6		100-100/6-13
Bacterial Indicators, 10^3 mpn/100 ml					
Total coliform	240	-	160		160 - 160
Fecal coliform	130	-	50		39 - 160
Fecal streptococcus	70	-	30		29 - 160

[a] Median EMC of all sites and storms within county-wide permit.
[b] Range of median EMCs of individual sites within each county-wide permit.
-= Not measured.
nd = Not detected.

capturing the smallest storms may underestimate the true annual discharge (if substantially large storms are not sampled). Moreover, 1994-95 was a very wet year. Rainfall was approximately double the long-term annual average which generated some of the largest peak flows in recent history (USGS 1995). The magnitude of bias associated with unsampled storm events cannot be assessed because none of the SCB monitoring programs have sufficient temporal sampling regimes to address this question.

Other temporal assumptions relative to this study that can introduce uncertainty are even less understood than flow-related correlations. Assumptions which are not well understood for southern California watersheds include relationships of water quality to antecedent dry periods (pollutant build-up) and rainfall intensity or duration (pollutant transport). Examples of the interactions between these two important parameters include concepts such as “first flush” (initial storm flows) or “seasonal flushing” (initial storms of the water year). Although several investigators have demonstrated portions of these concepts in other regions (Herricks 1995), they are not well-quantified in southern California. In some cases they appear significant (OCEMA 1996, RWQCB-LA 1988); in others, they do not (SCCWRP 1989).

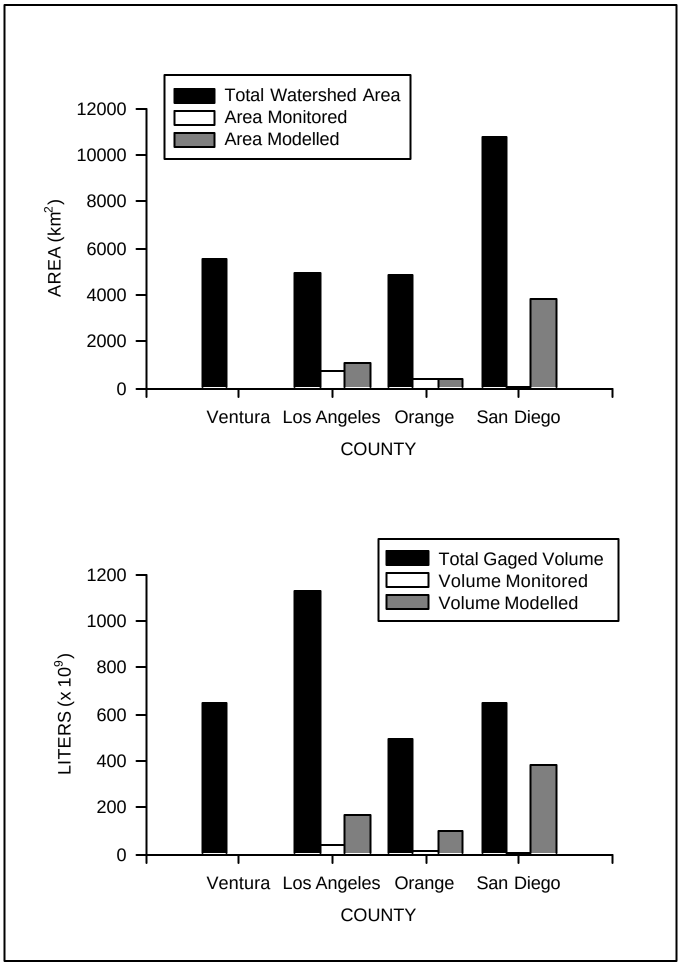
Temporal variability within and among runoff events is compounded in the SCB by the different sampling strategies utilized by stormwater monitoring agencies. Our data set was comprised of individual grab, single and multiple weighted-composite samples. Grab and compos-

TABLE 7. Estimates of regionwide constituent concentrations in urban runoff and mass emissions to the SCB during the 1994-95 water year.

	Regionwide Concentrations			Regionwide Mass Emissions		
	Units	Median	(10 - 90th percentile)	Units	Median	(10 - 90th percentile)
TSS	mg/l	205	(68 - 889)	mt^a x 10^3	598.4	(198.5 - 2,594.1)
Ammonia	mg/l	0.3	(0.1 - 1.1)	mt x 10^3	0.9	(0.3 - 3.2)
Nitrate-N	mg/l	3.0	(0.8 - 11.8)	mt x 10^3	8.8	(2.3 - 34.5)
Total Phosphate	mg/l	1.0	(0.2 - 4.1)	mt x 10^3	2.9	(0.5 - 12.0)
Chromium	µg/l	10	(4 - 34)	mt	29.2	(12.8 - 98.1)
Copper	µg/l	30	(10 - 85)	mt	87.6	(29.2- 249.3)
Lead	µg/l	13	(7 - 85)	mt	39.3	(19.2 - 246.9)
Nickel	µg/l	20	(<10 - 47)	mt	58.3	(<29.2 - 136.6)
Zinc	µg/l	108	(50 - 369)	mt	316.4	(146.0 - 1,076.2)

^{a}mt=metric tons

FIGURE 3. Total watershed area and volume discharged during the 1994-95 water year from rivers and creeks listed in NPDES stormwater permits of Southern California relative to the quantity actually monitored or estimated by permittees using stormwater management models.



ite samples, however, represent very different portions of a storm event. Grab samples represent a single snapshot of water quality during a storm event and, for the most part in 1994-95, were taken independently of flow regime or time since start of flow. Composite samples were actually multiple grab samples which, when combined together, were used to represent the mean water quality for an entire storm event. Composite samples, however, were weighted differently among the agencies. Some were weighted by storm flow (e.g., sampling every set volume interval); others were weighted by time (e.g. every hour, every 15 minutes, etc.). Flow-weighted composites sample more frequently during high flows than low flows, while time-weighted samples are distributed evenly throughout the storm event. Moreover, the number of samples per composite varied substantially among agencies (4 to 40+), or even within an agency (12 to 40+). The degree to which sampling strategies influence water quality results has not been quantified in terms of bias to the true EMC or the relative effect on seasonal loading estimates.

One reason we needed to rely on so many assumptions is that the monitoring programs are not entirely designed to estimate mass emissions to the ocean. Most monitoring programs have multiple purposes, all of which are important. Multiple information needs from urban runoff monitoring include regulatory compliance, identifying sources of pollutants and developing runoff models, as well as evaluating management actions such as effectiveness of best management practices (Dixon and Chiswell 1996). Even if calculating total pollutant loads to the marine environment were not the primary goal of urban runoff monitoring, we suggest that the same assumptions we had to make will also inhibit the use of current monitoring data for other purposes. For example, evaluating the effectiveness of a specific management action, would be very difficult with the degree of variation observed. If a load reduction of 30% is targeted, but variability in mass emission estimates are only accurate to within a factor of five to 10, true load reductions will be obscured and may not be detected. The effect of large variability would also hinder attempts to assess differences between sources and the variance added to a mass emissions computer modeling program would limit its utility as a management tool.

Estimating pollutant mass emissions from urban runoff discharges is the only way to gain perspective relative to the magnitude of inputs from other sources. Even when using the lower end of the mass emission estimates provided in this article, based upon monitoring data compiled from the 1994-95 NPDES permitted stormwater programs, inputs from urban runoff are substantial relative to other sources (See *Characteristics of Effluents from Power Generating Stations in 1995* and *Characteristics of Effluents from Large Municipal Wastewater Treatment Facilities in 1995* in this volume). Mass-based comparisons among various sources are preferred because large temporal and/or spatial changes in concentrations or flow can mislead scientists and resource managers when assessing the extent of potential impact. Of course, mass emission estimates are just one factor in the overall impact assessment process. Other important elements need to be considered including pollutant transport, contaminant fate, and biological impairment (See *Impacts of Stormwater Discharges on Santa Monica Bay* and *Toxicity of Stormwater Discharges from Ballona and Malibu Creeks* in this volume).

We suggest that estimating mass emissions is one of the greatest reasons to monitor because this is the only way in which stormwater management agencies can assess their relative contribution of pollutants to the marine environment. In southern California, marine environments are habitats of great concern since little freshwater habitat exists in our ephemeral streams and most channels are already highly modified. Currently, urban runoff is estimated to be a substantial source of pollutant inputs. However, this study has shown that mass emission calculations required numerous assumptions and the quality of load estimates are uncertain. If urban runoff is in fact a large source of pollutants, then quality load estimates will be required so that stormwater managers can leverage appropriate funding from their respective legislative bodies for controlling these inputs. If urban runoff is not a significant source of pollutant inputs, then quality load estimates will serve to alleviate the regulatory pressure and public perception that this source of inputs represents an unresolved environmental problem. At this point in time, the “true load” from creeks and rivers of the SCB is unknown. Furthermore, without adequate mass emission estimates and reliable confidence limits we will be unable to quantify with certainty whether mass emissions from urban runoff are increasing, decreasing, or staying the same with time, or whether they are changing as a result of management action.

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