Watershed-based Sources of Contaminants to San Pedro Bay and Marina del Rey: Patterns and Trends

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ABSTRACT

Contaminated sediments in harbor environments (ports and marinas) can lead to a variety of management concerns such as human health risk, ecologic effects, and costs of dredge material disposal. One of the most effective long-term strategies to managing contaminated sediment is to identify and control the main sources of contamination to the harbor. Although watershed-based sources are considered to be the predominant source, this has not been demonstrated quantitatively. Furthermore, synthesized information is needed on where contaminants are originating, what the typical ranges of inputs are, and how sources vary on an intra-annual and inter-annual basis.

This goal of this report was to collate and synthesize existing data collected on sources of pollutants to San Pedro Bay (Los Angeles and Long Beach Harbors) and Marina del Rey in order to quantify the magnitude of inputs, assess the relative loading among the various pollutant sources, and identify key data gaps. Hydrologic, water quality, and land-use data from Los Angeles County was combined with data and model output compiled by SCCWRP to analyze patterns and trends in loading.

Data confirmed that the largest source of contamination to San Pedro Bay is watershed-derived loading from the Los Angeles River and Dominguez Channel watersheds. The Los Angeles River watershed contributes the greatest overall mass loading, but the Dominguez Channel watershed contributes the largest proportional loading (i.e. loading normalized for watershed size). In general, industrial and residential land uses are the largest contributors of contaminants. Data from the 1990s also revealed that dry-season (i.e. non-storm) loading may comprise a significant portion of total annual loading, and in dry years, can be the predominant source of contaminants to the harbor. Analysis of temporal trends in the data showed that metals loading has not substantially changed since the 1970s, but loading of DDT and PCBs has declined.

Annual loadings of metals vary between 10^3 and 10^5 kg/year, with zinc and copper loading typically exceeding loads of other metals. Variations in annual loading appear to correspond with changes in rainfall and runoff; however, direct analysis of the relationship between rainfall intensity and duration and loading produced only weak correlation coefficients. This correlation would likely be improved by analyzing a larger data set on more homogenous land use types.

Key data gaps in our understanding of contaminant loading to the harbor include the lack of data on loading of PAH and pesticides, lack of long-term data on dry season loading, lack of information on inputs from the Dominguez Channel Watershed, and the need for more temporally resolved loading data from specific land use types. Information on the transport and fate of runoff-derived contaminants within the study area are also needed to improve estimates of the impact of loadings on sediment contamination.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Contaminated sediments in harbors (e.g., ports and marinas) can lead to numerous problems, including ecological, human health, and port commerce impacts. Ecological impacts include degradation of habitat quality, toxicity to biota, alterations in community structure and diversity, and even declines in total abundance of organisms. Regional monitoring of the Southern California Bight has identified a disproportionate amount of impaired sediment quality in ports and marinas relative to other areas of the region (Noblet et al 2002). Human health impacts arise from contaminated sediments when some pollutants are transferred from sediments to biota and, eventually, to fish that are consumed by anglers. There is only one location in southern California where there is an advisory for consumption of seafood; the area from the Port of Los Angeles (POLA) to Pt. Vicente (Palos Verdes) has a seafood consumption advisory as a result of bioaccumulation of total DDT in white croaker (*Genyonemus lineatus*). Contaminated sediments also impact port commerce by increasing the cost of dredging activities for port maintenance or renovation; disposal of contaminated dredged materials is an order of magnitude more costly than uncontaminated sediments.

There are a myriad of sources that can contribute pollutants to contaminated sediments within harbor systems. In harbors from the Los Angeles region, for example, sources of contaminants include direct discharge to the harbor from ships, runoff from container yards and other port areas, surrounding watershed-based runoff conveyed through the Los Angeles (LA) River or Dominguez Channel, direct aerial deposition, and point source discharges within the harbor such as wastewater treatment plants or industrial facilities. The relative contribution of each of these sources to sediment contamination has not been quantitatively compared and the timing of the emissions from some of these sources is not well understood.

One of the most effective strategies for controlling sediment contamination in harbors is to identify and abate the source(s) of pollution that contributes to the sediment contamination. The most efficient strategy would first focus on the largest source(s). Although some data exists to begin to answer this question, the data has not be compiled and analyzed in a comprehensive manner. In general, watershed-based sources are considered to be the predominant source, but this has not been demonstrated quantitatively. In addition, there are differences not only in the magnitude, but the timing and delivery of contaminants to harbor areas. To manage sources, decision makers will need to understand where contaminants are originating, what the typical ranges of inputs are, and how sources vary on an intra-annual and inter-annual basis.

The main goal of this report is to collate and synthesize existing data collected on sources of pollutants to San Pedro Bay, which includes Los Angeles Harbor and Long Beach Harbor, and Marina del Rey in order to quantify the magnitude of inputs, assess the relative loading among the various pollutant sources, and identify key data gaps. An emphasis is placed on collating data and estimating loads from the LA River and Dominguez Channel watersheds to San Pedro Bay and from Ballona Creek to Marina del Rey. Within the realm of runoff sources, we will investigate which watershed is the greatest contributor, if there are predominant sources (e.g. land uses) within these watersheds, and if there are patterns in loading over time (i.e. dry versus wet weather, interannual variation, interstorm variation). Managers can then use this information to help manage contaminated sediments by either focusing their efforts on the largest contributors of pollutants, on the times and places of greatest pollutant inputs, or to identify the critical data gaps that still exist in order to achieve meaningful pollutant loading reductions.

METHODS AND DATA SOURCES

This main goal of this report is to evaluate patterns and trends in the loading of contaminants (i.e. trace metals and organic compounds) from the watersheds that drain into San Pedro Bay and Marina del Rey. Key questions addressed by this report are:

- What are the predominant sources of contaminants?
- What are the long-term (i.e. decadal) trends in annual loading?
- What is the typical range of annual loading that should be expected?
- Which watersheds typically contribute the greatest annual loading?
- What land use types are the largest contributors to annual loading?

These questions were addressed by analyzing existing data and conducting limited modeling of watershed loading patterns. A variety of data sources were used to characterize inputs to the study area and identify data gaps. The primary data sources were the Los Angeles County Department of Public Works (LADPW) hydrology and water quality reports and SCCWRP databases and annual reports. Discharge data from Publicly Owned Treatment Works (POTW) and industrial discharges were from self-reported data under NPDES permit requirements. In all cases, metals data are reported as total metals.

Hydrology data (i.e. runoff volumes) were compiled from the LADPW hydrologic reports from 1996-2002. Annual and wet season runoff volumes were used as reported. Dry season runoff volumes were calculated as the difference between the measured total annual and wet season discharge volumes.

Storm water quality data were compiled from the LADPW Storm Water Quality Monitoring Reports from 1996-2002. Data was generated by LADPW using their GIS-based model that uses measured runoff concentrations from established land-use sites and rainfall isohyets to estimate loading. The loading from the subset of measured storms were extrapolated to annual loading based on the total annual precipitation. Although, not specified in the LACDPW report, it appears from the text that the model is a static model based on the Rational Method[1] and the concentrations are measured using flow-weighted composite grab samples.

Annual loads were estimated by SCCWRP for three distinct time periods prior to 1996 (1971-72, 1979-80, 1986-87, and 1987-88) using a ratio estimation technique. This approach estimates annual loads based on the relationship between loads from a given time period and flow from that period, extrapolated over the course of the entire storm season. Although this method is a simplification, it provides the ability to estimate annual loads with limited historic data. More detailed discussion of this method, its assumptions and shortcomings can be found in SCCWRP (1992).

Long-term average wet weather loads were estimated/modeled by using long-term rainfall estimates from the Los Angeles International Airport rain gauge and applying standard runoff coefficients to land use distribution area to estimate volumetric loadings (Ackerman and Schiff, 2003). Land use data was obtained from LACDPW, long-term rainfall estimates were from

[1] The Rational Method calculates total runoff from a given storm based on the catchment area, rainfall intensity, and a runoff coefficient that accounts for the amount of runoff typically associated with the specific land use types.

PRISM, watershed definitions were from CALWATER 3.0. Land use distributions within each sub-watershed were calculated in GIS and the average 30-year annual rainfall was applied to the centroid of each sub-watershed.

Dry weather water quality data was estimated by extrapolating concentrations measured by SCCWRP in 2000 and 2001 from the Los Angeles River at Wardlow Road (Ackerman et al., 2003). Composite samples from both years were averaged to provide an estimate of dry season concentrations. Dry season loads were estimated by multiplying the average concentration by total dry season discharge, as reported by LACDPW. Dry and wet season loading were combined to provide an estimate of total annual load.

RESULTS AND DISCUSSION

Contaminant loading to San Pedro Bay and Marina del Rey (study area) is influenced by various sources/inputs from the Los Angeles River, Ballona Creek, and Dominguez Channel watersheds. Effective management or remediation of this loading depends on understanding the distribution and temporal patterns of these sources. This section is organized around the key questions that determine loading patterns to the study area. The answer to each question is followed by a discussion of the implications of the data, potential use of the data in a management context, and caveats that must be considered when using the data. Finally, we discuss data gaps and unanswered questions necessary to more fully understand loadings.

What is the most predominant source of contaminants to the study area?

Understanding the relative contribution of loading from the main sources is the first question that must be addressed when considering contaminant sources to the bay. Knowing the predominant sources will allow focused investigation of more precise patterns in the data and development of targeted management strategies.

Watershed-based sources include dry weather and storm water runoff conveyed by the LA River and Dominguez Channel to San Pedro Bay. In addition, there are four industrial dischargers and one POTW that discharge directly to the study area. Annual discharge data is available for POTW and industrial discharges; however, only storm water runoff data (not dry season runoff) is available for the rivers that drain to the study area. The Terminal Island POTW on Terminal Island in Long Beach is the only direct POTW discharge to San Pedro Bay. There are four industrial facilities that discharge directly to San Pedro Bay or within the tidal prism of the bay. The majority of total loading to the study area results from discharge from the Los Angeles River (Table 1), with the POTW and industrial discharges accounting for approximately 20% of the annual (wet weather) volume, 4.8% of the total zinc, 4.0% of the total annual copper, and less than 1% of all other constituents analyzed.

Table 1. Contribution of Various Sources to the Total Load of Various Constituents to San Pedro Bay. Data was obtained from routine NPDES self-reporting for 2000-01. Loading data for the Los Angeles River and Dominguez Channel includes only storm water; dry season discharge was not available. NR = not reported, ND = not detected.

	Total Load (kg)	Percent of Total Load			
		Los Angeles River Wet Weather	Dominguez Channel Wet Weather	Terminal Island POTW	Industrial Discharge
Suspended Solids	2.59E+07	81.2%	18.7%	0.1%	0.0%
Copper	2.07E+03	67.9%	28.0%	4.0%	0.1%
Lead	9.75E+02	90.1%	9.8%	**ND**	0.1%
Zinc	1.26E+04	44.7%	50.0%	4.8%	0.5%
Aluminum	6.43E+04	77.1%	22.9%	**NR**	0.0%
Nickel	8.29E+02	84.5%	14.9%	**ND**	0.6%
Volume (m3)	1.10E+08	78.3%	**NR**	20.0%	1.7%

Wet weather data for the Los Angeles River and Dominguez Channel were obtained from the LACDPW 2000-01 Annual Monitoring Reports and consist of composite grab samples from six storms. These extrapolations, likely underestimate the actual annual load because they did not capture every storm during the 2000-01 season, and should be considered general approximations only. In addition, our estimation of total contaminant loading was limited by the lack of data for PAHs and pesticides in the LACDPW reports[2]. Data on loadings to the study area (shown in Table 1) does not include direct aerial deposition, direct discharge from ships, leaching from anti-fouling paints, or discharge from proximate sources, such as container yards[3]. Finally, data on dry weather flow were not available except for in the Los Angeles River (see next section); consequently, the dry weather component of total annual load could not be included in Table 1. However, inclusion of dry weather loading data would not be expected to affect the general conclusion that loadings from the watersheds via the three channels is the predominant source of contaminants to the study area.

What is the proportion of dry weather vs. wet weather discharge?

Contaminants are discharged from watershed-based runoff to the study area during both the wet and dry seasons. Approaches for controlling wet weather loading differ from those for dry season loading. To better focus management and regulatory decisions, it is important to understand the relative proportion of wet vs. dry season loading.

We analyzed reported LA River and Ballona Creek wet and dry season discharge data for the 2000-01 and 2001-02 seasons (dry season data were not available for Dominguez Channel). For both these years, the majority of the total annual volume discharged from the Los Angeles River and Ballona Creek occurred during the dry season; however, the majority of the solids were discharged during the wet season (Figure 1). Relative loading of contaminants vary by constituent. For both the Los Angeles River and Ballona Creek, the majority of lead and aluminum were discharged during the wet season. In contrast, zinc, nickel, and copper loading were more evenly distributed between the wet and dry season. For each of these metals, the dry season contribution to total loading was more prevalent in the Los Angeles River than in Ballona Creek. This difference can likely be attributed to the presence of POTW discharge in the Los Angles River. Approximately 72% of the 276 million m^3 of dry season flow in the Los Angeles River was contributed by the POTWs that discharge directly to the river or its major tributaries, with the balance being contributed mainly by storm drains, groundwater exfiltration, and tributary inflow. In contrast, there is no POTW discharge to Ballona Creek; therefore, it receives proportionately less dry season flow and load than the Los Angeles River. No data were reported for DDT, PCBs, or mercury. Use of these three constituents is highly restricted; therefore, they are likely discharged at levels below the detection limits. It should be noted that in relatively dry years, such as 2001-02 the influence of dry urban-derived flows is typically more prevalent (Choi et al. 2003).

Differences between wet vs. dry weather discharge and loading must be viewed with limited confidence at this time due to the low sample size. As discussed previously, wet weather data was derived from two years of monitoring data from LACDPW. Dry weather loading was

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[2] Data for DDT and PCBs was included in some reports, but was not detected in the storm water samples.
[3] Analysis of these "direct" discharges is not the intended focus of this report; however, these sources may contribute contaminant loading to the study area.

estimated by extrapolating concentrations measured during two sampling events over the entire dry season. Wet weather discharge and loading can vary dramatically from year to year, with intermittent flashy systems such as those that occur in Southern California having the greatest variation (Poff et al., 1989). Similarly dry season discharge and loading can vary with changing land use and management patterns in the watershed. For example, Hamilton (1992) documented average dry season flow in Ballona Creek to vary by up to 180% between 1970 and 1980. Such variations can dramatically alter the distribution of loading between the wet and dry season on a year-to-year basis. Longer term data sets should be obtained and analyzed to more clearly define the relationship of dry vs. wet season loading and determine if trends are consistent from year to year.

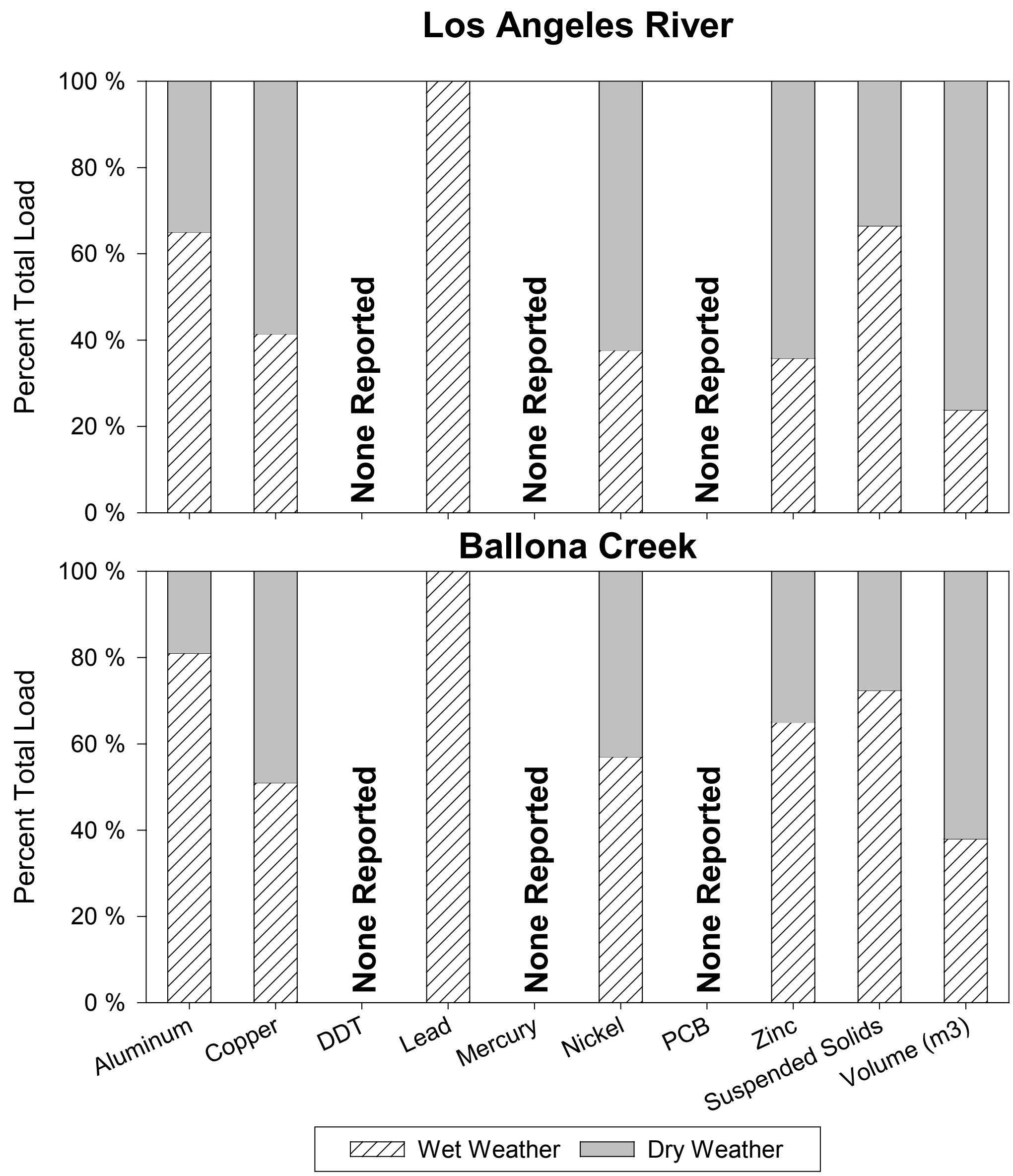

Figure 1. Comparison of Dry Season vs. Wet Season Contaminant Loading. Gray bars represent proportion of total annual load resulting from dry season runoff, white hatched bars represent proportion of total annual load resulting from storm water runoff. Data from Los Angeles County Department of Public Works, 2000-01 and 2001-02 storm water monitoring data and hydrology reports (i.e. gauge data).

Differences in the relative proportion of dissolved vs. particulate metals must also be considered when comparing the contribution of wet vs. dry season loading. The vast majority of wet weather metals loading typically occurs in the particulate phase. Young et al. (1980) observed that between 88% and 100% of storm water metals loading in the Los Angeles River occurred in the particulate phase. A similar pattern can be observed in the LADPW storm water monitoring reports, which typically report between 60% and 90% of storm water metals loading as particle-bound. In contrast, preliminary dry season data collected from Ballona Creek during the summer of 2003 showed that between 45% and 90% of metals occur in the dissolved phase.

The relative proportion of particulate vs. dissolved metals has implications for both sediment contamination and bioavailability of toxic compounds. Particle-bound pollutants are more likely to settle near the mouth of channels such as the Los Angeles River and contribute to sediment contamination. In contrast, dissolved metals may have higher bioavailability and pose a greater risk for toxicity. However, the transition from fresh water to salt water at the mouth of the river may affect the speciation of metals and subsequent partitioning or flocculation. The sorption-desorption kinetics of metals along salinity gradients such as the mouth of the Los Angeles River would need to be investigated further to better understand the precise fate of dissolved vs. particulate metals in the harbor.

How does storm size affect concentration of contaminants in storm water?

Previous studies have documented that rainfall intensity and duration can affect runoff and loading from watersheds to coastal streams (Ackerman and Weisberg, 2003; Tiefenthaler and Schiff, 2003). Given the variability in storm patterns in the Los Angeles Basin, understanding this relationship is important to developing effective management strategies. For example, management of loading from small storms can be accomplished using small-scale treatments, such as filters, basins, or wetlands, whereas management of loading from large storms may require larger detention basins or other facilities.

Given the inherent spatial variability of rainfall patterns, relationships between precipitation and loading are easier to discern in smaller more homogenous watersheds where characteristic rainfall data is available. Therefore, we investigated the effect of storm size in the Ballona Creek watershed, which is substantially smaller than the Los Angeles River watershed.

Mass loading typically increases proportional to storm size (see next two sections). To discern patterns in contaminant concentration relative to storm properties, we investigated the effect of rainfall intensity, duration, and antecedent dry days on the concentration of contaminants in Ballona Creek storm water, but found no clear relationships. Figure 2 illustrates the relationship between storm intensity and duration and the concentration of solids and copper, which is representative of the results seen in all the data analyzed. Although there appears to a subtle pattern of decreasing copper concentration with increasing rainfall intensity, the correlation is weak (all $R^2 < 0.15$).

Although the available data does not allow us to draw meaningful conclusions, more refined analysis may reveal clearer patterns. Our analysis used rainfall data from the rain gauge at Los Angeles Airport compared to flow-weighted mean concentrations from composite samples collected by the Los Angeles County Department of Public Works as part of their NPDES monitoring. Therefore, any relationships between rainfall and concentration in storm water discharge will be confounded by temporal and spatial differences between the two data sources (i.e. a time lag between the period of reported rainfall and when the composite storm water samples were collected, lack of temporal resolution in rainfall data). Other studies have shown a direct positive relationship between rainfall intensity or duration and pollutant wash off (Vaze and Chiew, 2003; Tiefenthaler and Schiff, 2003). For example, Vaze and Chiew (2003) found that both the total wash off load and concentration of TSS, total nitrogen, and total phosphorus increased with increasing rainfall intensity. Although longer rainfall duration also resulted in increased wash off load, the effects were not as dramatic as with increased rainfall intensity (Vaze and Chiew, 2003). More resolved rainfall and runoff data from smaller, homogenous catchments will be necessary to appropriately address these relationships in the local watersheds.

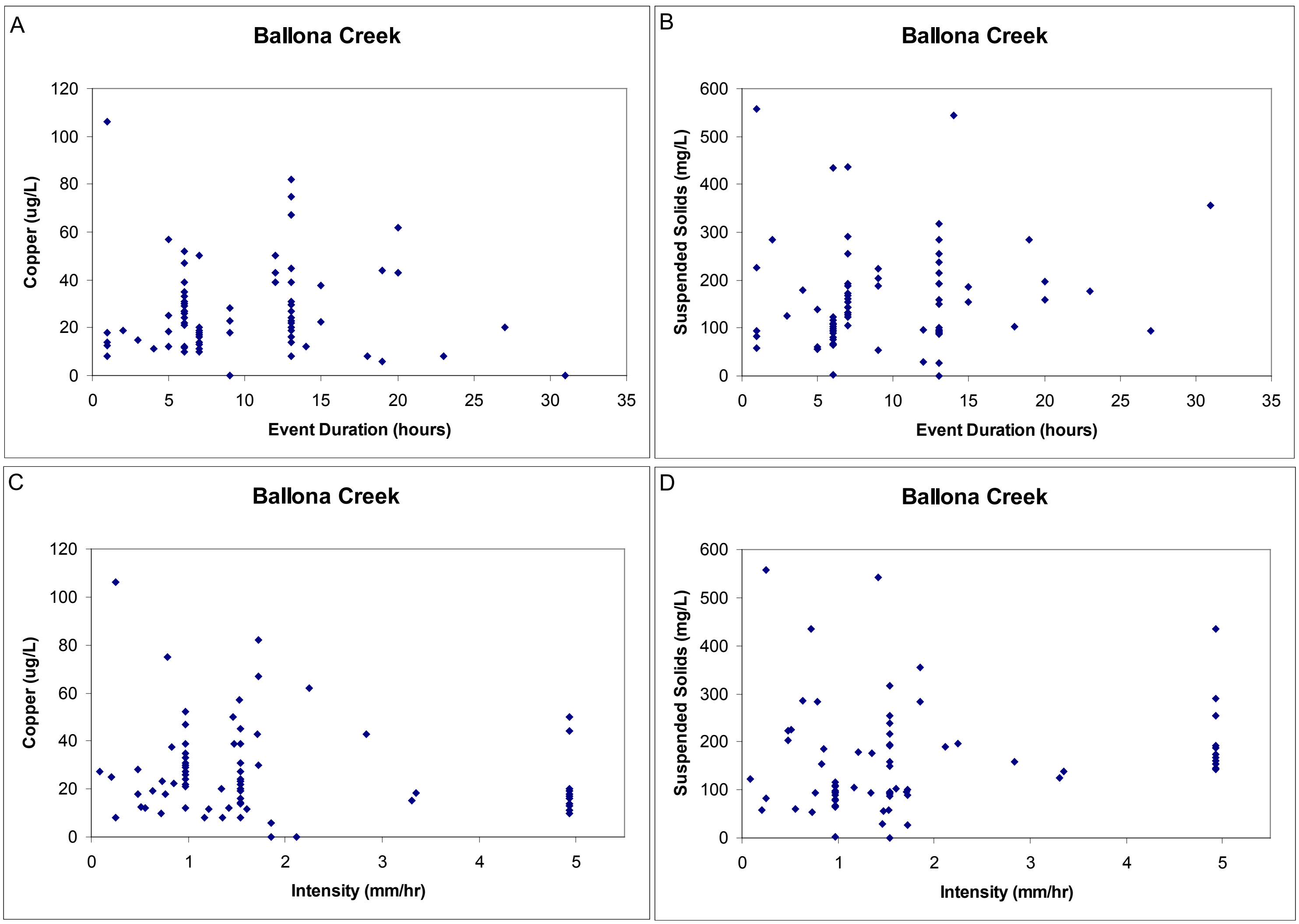

Figure 2: Effect of Rainfall Duration and Intensity on Concentrations of Copper and Suspended Solids in Ballona Creek Storm water. Top graphs show the effect of rainfall duration on concentration of copper (panel A) and suspended solids (panel B) in Ballona Creek. Bottom graphs show the effect of average rainfall intensity (mm/hr) on concentrations of copper (panel C) and suspended solids (panel D). Rainfall data from the Los Angeles Airport rain gauge. Storm water data from Los Angeles County Department of Public Works Monitoring Reports from 1996-1999 storm seasons.

What are the long-term (i.e. decadal) trends in annual loading?

Contaminants in harbor sediments may result from recent watershed-derived runoff, historic runoff, or a combination of the two. Similarly, trends in contaminant loading may vary over time in response to changes in watershed land use practices. Understanding the temporal trends in loading is important to determining which constituents should be given priority when developing management strategies.

We investigated temporal trends in wet-weather contaminant loading in two ways. First we plotted available data on annual loading of metals and organics from the 1970s, 1980s, and 1990s (Figure 3 and Table A1, Appendix A). Second, we plotted the total annual load of various contaminants against the total annual volume discharged from the Los Angeles River. This analysis allows for an investigation of trends in loading independent of the effects of variation in volume. If the concentration of a constituent remains constant over time, the slope of the graph will be constant. Changes in concentration over time will be reflected by a parallel change in the slope of the graph. Increasing concentration trends will result in an increasing slope and decreasing concentration will result in a decreasing (or flat) slope (Figure 4).

Long-term trends for metals loading have not varied considerably over time as indicated by the consistent relationship between annual load and runoff volume seen in Figure 4. Figure 3 also illustrates that variations in annual metals loading correspond strongly with variations in annual runoff volume, with wetter years having higher loading. In contrast, data for DDT and PCBs appear to have decreased over time, as reflected by the flat, or decreasing, slope of the load vs. volume plot. For example, 1971-72 and 1986-87 had similar amounts of total runoff. However, the PCB and DDT loading in 1971-72 was approximately 7 to 10 times as higher than in 1986-87, indicating a general decrease in loading over time. This trend is not unexpected, since use of DDT and PCB has been banned since the early 1970s.

The general trends shown in Figures 3 and 4 are credible. However, the actual estimates of annual load used to investigate long-term trends contain considerable uncertainty. Annual loads were extrapolated over the course of an entire season using concentration data from a limited number of storms combined with annual runoff data. Extrapolation of data from several storms to an entire season assumes that storm conditions are relatively constant over the course of the season. This erroneous assumption may result in over or under-estimation of total annual load, depending on the conditions present during the storms that are sampled (e.g. rainfall intensity, duration, and antecedent moisture conditions). Furthermore, long-term comparisons were made using a variety of data sources, collected and analyzed in a variety of manners. Early data from 1971-72, 1979-80, and 1986-88 are from SCCWRP annual reports, while later data from 1996-2002 are from Los Angeles County Department of Public Works. Uncertainty associated with different data sources is exacerbated by differences in detection limits (DL) used by SCCWRP (2 ng/l) vs. LADPW (100 ng/l). The higher DL used by LADPW in recent monitoring could be masking the actual trend (or lack thereof); however, storm water monitoring conducted by SCCWRP during 2002 and 2003 also resulted in non-detect values for DDT and PCBs. Therefore, the trends shown in Figure 3 and 4 are likely real. However, given the different data sources and extrapolation methods, the resultant trends should be considered general estimates only.

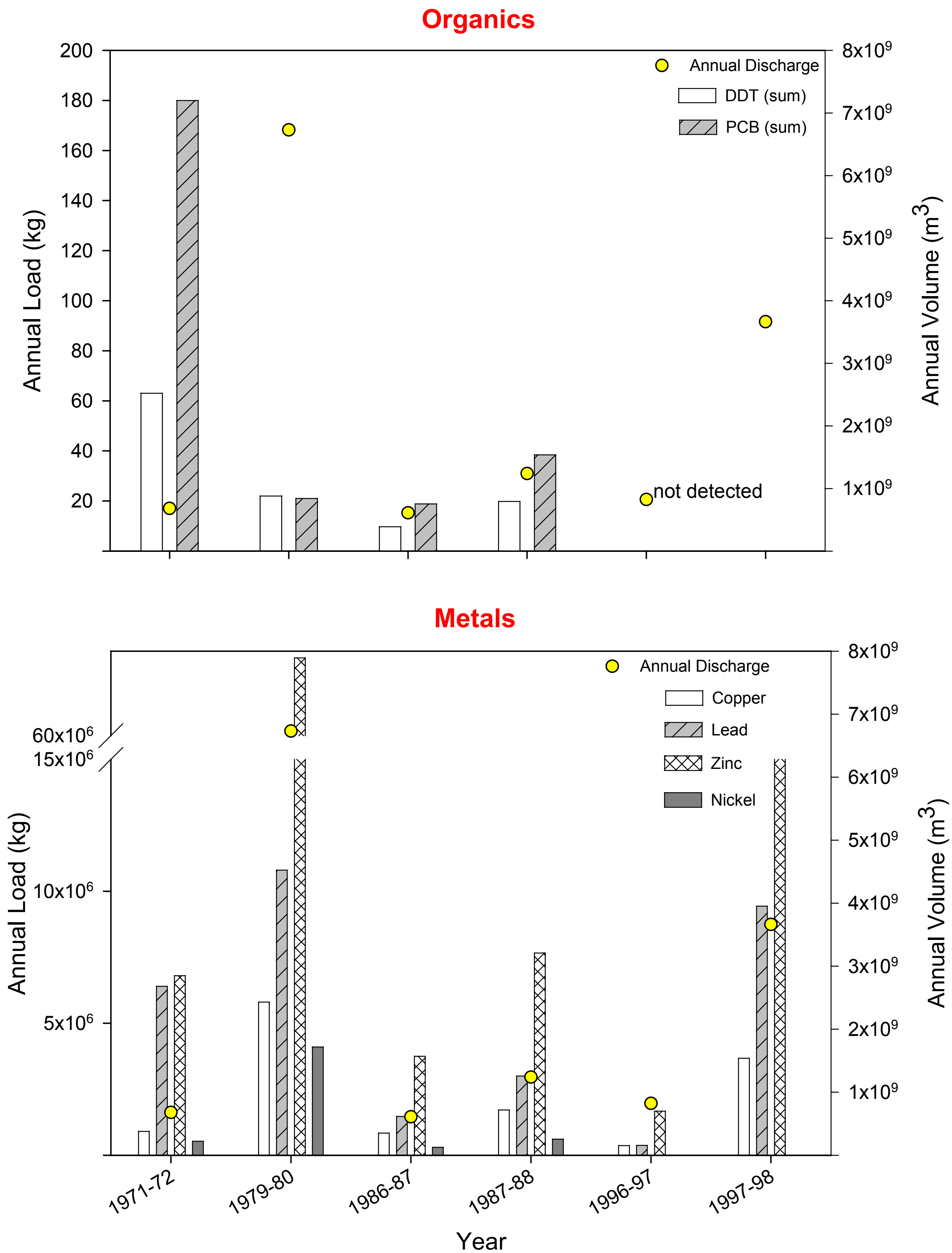

Figure 3: Annual Wet Weather Mass Emission From the LA River Over Time, 1971-1998. Long term trends in annual loading of metals and organics based on available data from discrete time periods during the 1970s, 1980s, and 1990s. Annual runoff volume for each year is indicated by points above each set of bars. Data from 1971-72, 1979-80, 1986-88 (SCCWRP), and 1996-2002 (LACDPW). Detailed data are shown in Table A1, Appendix A.

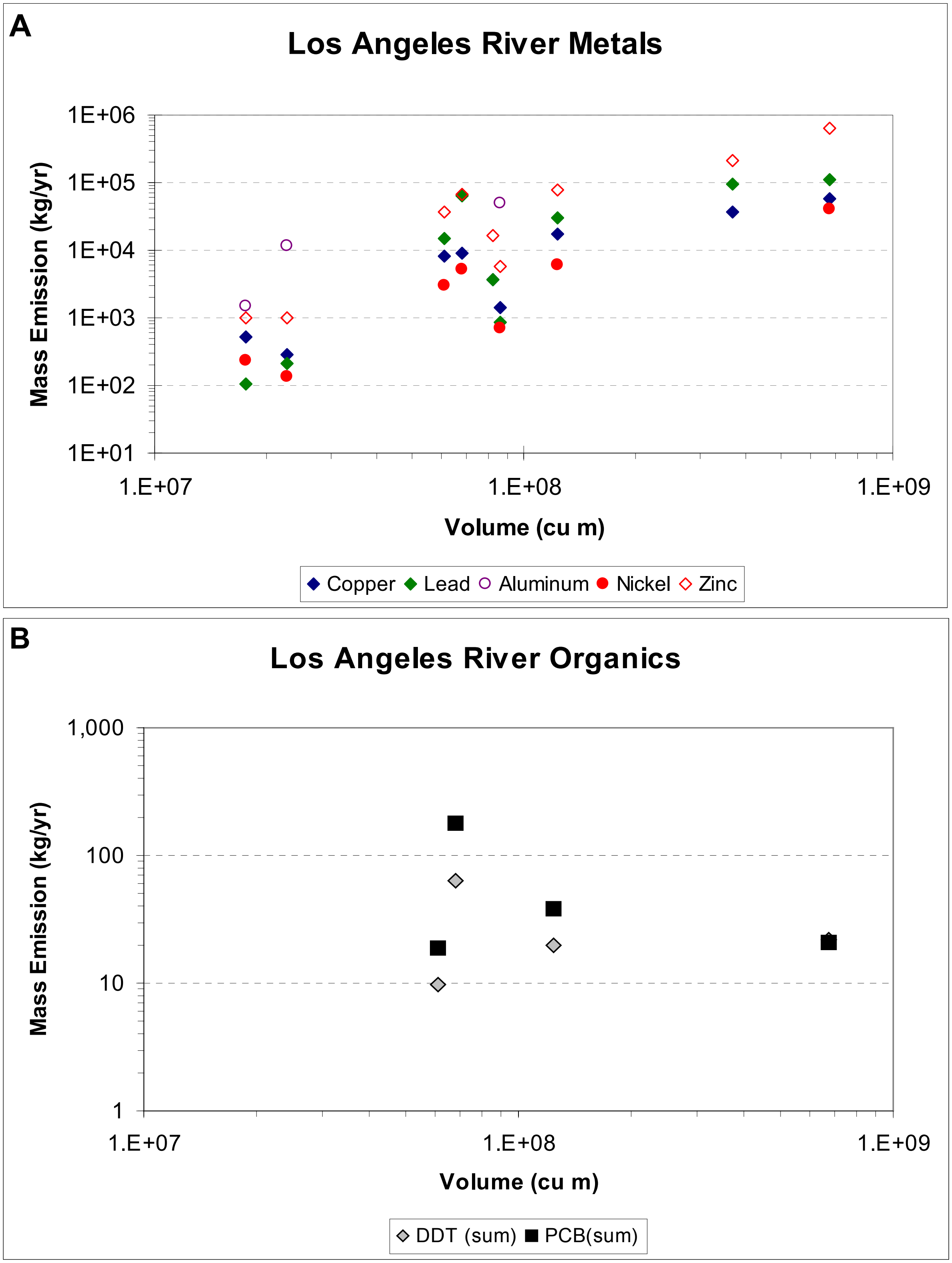

Figure 4. Annual Wet Weather Mass Emissions vs. Annual Volume for the Los Angeles River. Long-term trends in mass emissions represented as annual load (kg) vs. annual volume (m^3) for metals (panel A) and organic compounds (panel B). Constant slope indicates constant temporal trends. Decreasing or flat slope indicated decreasing. Data from 1971-72, 1979-80, 1986-88 (SCCWRP), and 1996-2002 (LACDPW). Detailed data are shown in Table A1, Appendix A

What is the typical range of annual loading that should be expected?

The long-term temporal trends in loading are primarily a function of volume for most trace metals (Figure 3). However, annual variation can still be expected due to differences in storm patterns and subtle changes in land use practices. Understanding the typical range of variation allows more accurate differentiation of long-term trends from annual fluctuations and provides a range of values for use in developing management strategies.

The expected range of inter-annual variation in storm water loading was estimated by analyzing data from the past 5 years. Between 1996 and 2002, annual loads for lead, zinc, and copper varied[4] by 10^4 - 10^5 kg in the Los Angeles River and by 10^2 – 10^3 kg in Dominguez Channel and Ballona Creek (Figure 5). Patterns in annual variation appear to correspond with changes in rainfall and runoff. For example, in 1997-98 rainfall was the highest in 30 years, and more than double the 30-year season average. This high rainfall corresponds to high runoff volume and loading during that year. If the data from 1997-98 are removed from the analysis, the range of variation decreases to one to two orders of magnitude.

Annual loading was generally higher from the larger Los Angeles River watershed than it is from the smaller Dominguez and Ballona watersheds (Figure 5, Table A1, Appendix A). This pattern is more pronounced in years with greater rainfall when greater variability is observed. Given the relationship between variation in rainfall and loading, it is not surprising that the relatively large, heterogeneous Los Angeles River watershed exhibited a wider range of variation than the smaller, more homogenous Dominguez and Ballona creek watersheds. Therefore, management strategies should account for variations of up to four orders of magnitude in volume and loading on a relatively regular basis.

The data used to analyze short-term temporal trends in loading probably underestimates the true inter-annual variability. Estimates of annual load were taken from LADPW monitoring reports, which reported modeled loads. The modeled loads were based on measured concentrations from land use sites during several storms and rainfall isohyets, extrapolated over the course of the entire storm season. Consequently, the true annual variation is probably higher than indicated by the reported data due to factors, such as random differences in the specific storms measured each year (e.g. size of the particular storm, antecedent moisture conditions). Furthermore, these reports do not include data on dry season loading; however, in most watersheds we would expect less inter-annual variation in dry season runoff and loading than is observed in storm water runoff. Therefore, planning efforts should account for slightly higher annual variability than shown in Figure 5.

[4] The difference between the highest and lowest annual wet weather loads is between 10^4 - 10^5 kg in the Los Angeles River and by 10^2 – 10^3 kg in Dominguez Channel and Ballona Creek.

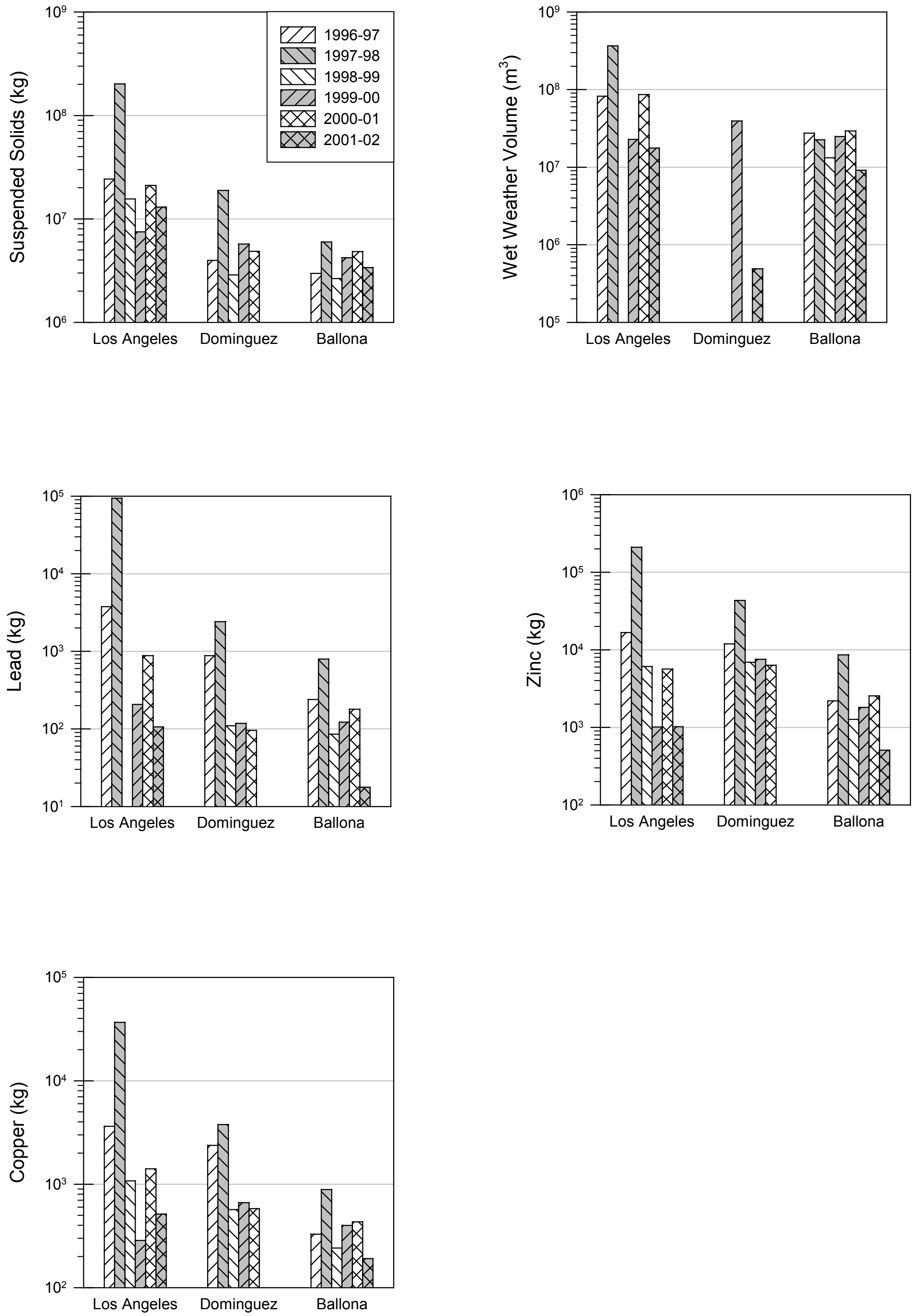

Figure 5. Annual Wet Weather Loads And Volume from Los Angeles River, Dominguez Channel, and Ballona Creek. Bars represent reported annual loadings for each storm season (kg) or estimated annual volume of runoff (m^3), shown on log scale. All data is from LACDPW annual monitoring report. Hydrology data is measured flow, water quality is modeled, based on the land use runoff data collected for each year. Detailed data are shown in Table A1, Appendix A

Which watersheds typically contribute the greatest annual loading to the study area?

From a management perspective, it is important to understand which of the watersheds that drain into San Pedro Bay typically contribute the largest load of various constituents, and how these loads compare to those discharged from Ballona Creek into Marina del Rey. Long-term average wet weather loads were modeled using 30-year rainfall data from PRISM (Daly and Taylor, 1998), land use runoff data from LADPW, and land-use distribution data from SCAG (1993). The resultant "typical" annual loads to San Pedro Bay (i.e. the combined load from the LA River and Dominguez Channel) range from 70 kg/year for cadmium to 49,748 kg/year for zinc. Typical annual loads to Marina del Rey from Ballona Creek range from 7 kg/year for cadmium to 6,901 kg/year for zinc (Figure 6 and Table A2, Appendix A). Consistently high zinc loadings likely result from the ubiquitous nature of zinc (from tires, galvanized metal, and other industrial uses) in the watersheds, compared to other metals. Suspended solid loadings typically range from approximately 3,000 metric tons/year from Ballona Creek and Dominguez Channel to 32,000 metric tons per year from the Los Angeles River.

In general, the 2,160 km^2 Los Angeles watershed contributes between five and ten times the annual load of various constituents as compared to the 338 km^2 and 187 km^2 Ballona and Dominguez watersheds. Consequently, the vast majority of loading to San Pedro Bay comes from the LA River vs. Dominguez Channel (Figure 7). This pattern results primarily from the difference in size of the watersheds, but may also be influenced by the distribution of different land uses in the watersheds (see next section).

The proportional contribution of each watershed to total loading to the study area was investigated by normalizing long-term average wet weather loads to watershed size (Figure 8 and Table A3, Appendix A). Normalized loading was consistently higher for the Dominguez Channel watershed compared to Los Angeles River. For most constituents, Dominguez Channel produced approximately 50% greater proportional loading. However for cadmium, copper, lead and zinc, proportional loading from Dominguez Channel was approximately double that of the LA River (and Ballona Creek). This pattern may be attributable to the predominantly industrialized nature of the Dominguez Channel watershed.

It is important to note that Figures 6, 7, and 8 represent only wet season data. Routine monitoring of dry season runoff has only occurred in the last several years so long-term dry-season data is not available. As discussed earlier, dry season loading can constitute up to 60% of the total annual load for some metals. Furthermore, the relative distribution of dry vs. wet season loading has likely changed over the last 30 years due to changes in land use patterns and management of WRP discharges. It is reasonable to assume that the larger Los Angeles River watershed will produce greater dry season loading than the smaller watersheds because of the greater amount of developed area and the presence of year-round POTW discharge to the river[5]. However, the magnitude of difference for each metal is impossible to estimate at this time. Therefore, the average wet season loadings shown in Figure 6 constitute a fraction of total annual loading to the study area.

[5] There are no POTWs that routinely discharge to Dominguez Channel or Ballona Creek.

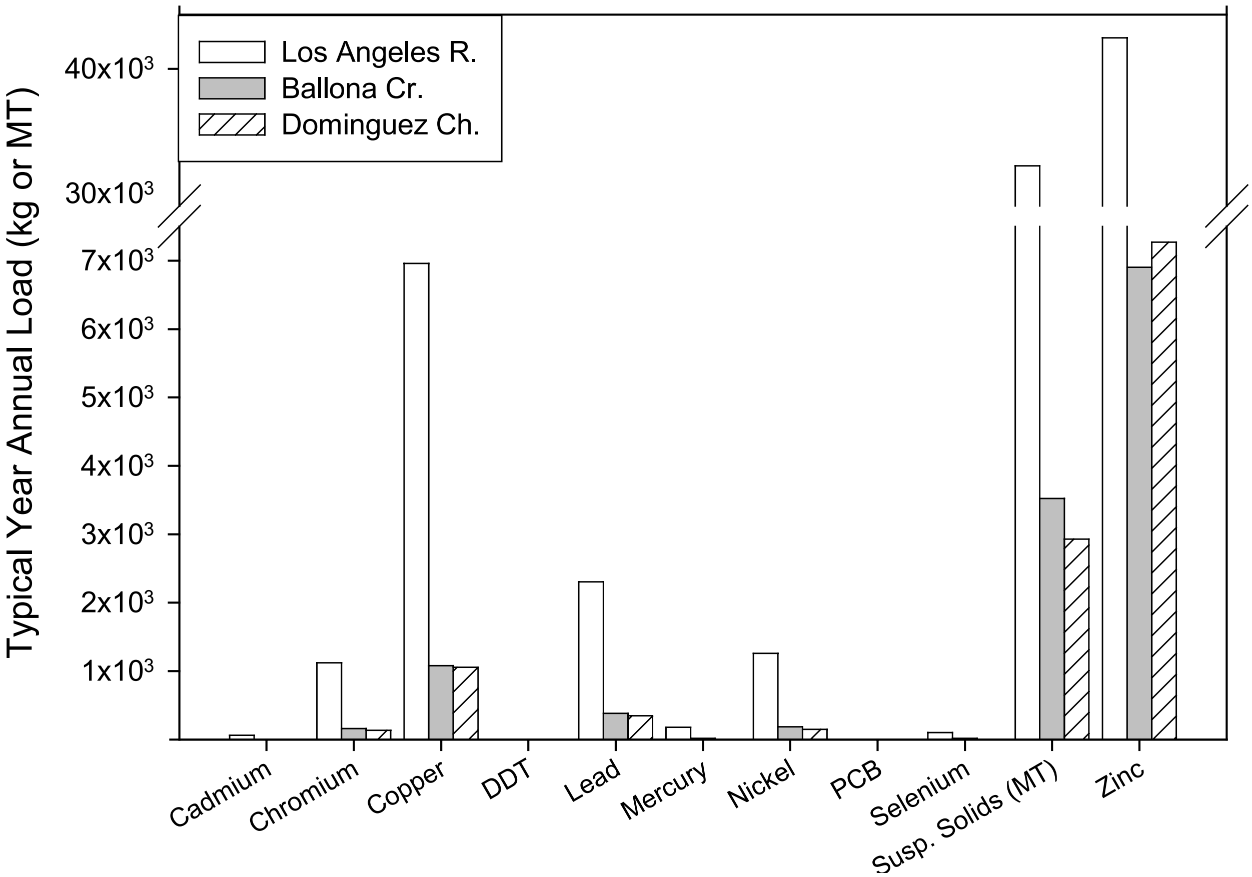

Figure 6. Typical Annual Wet Weather Loading to the Study Area From Various Watersheds. Bars show 30-year average loading from Los Angeles River, Ballona Creek, and Dominguez Channel. Data are modeled from 30-year average rainfall, land use runoff data, and land use distribution data. Metals and PCB data are in kg and suspended solids data are in metric tons. Detailed data are shown in Table A2, Appendix A.

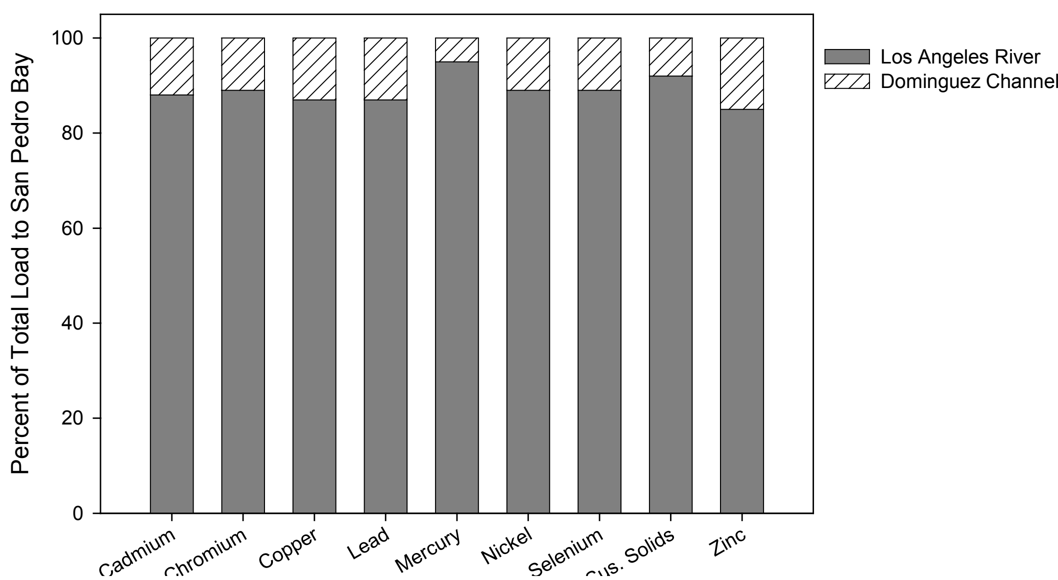

Figure 7. Distribution of Total Wet Weather Loading to San Pedro Bay. Percent of total wet weather loading from the LA River (grey bars) vs. Dominguez Channel (hatched bars). Data are modeled from 30-year average rainfall, land use runoff, land use runoff data, and land use distribution data.

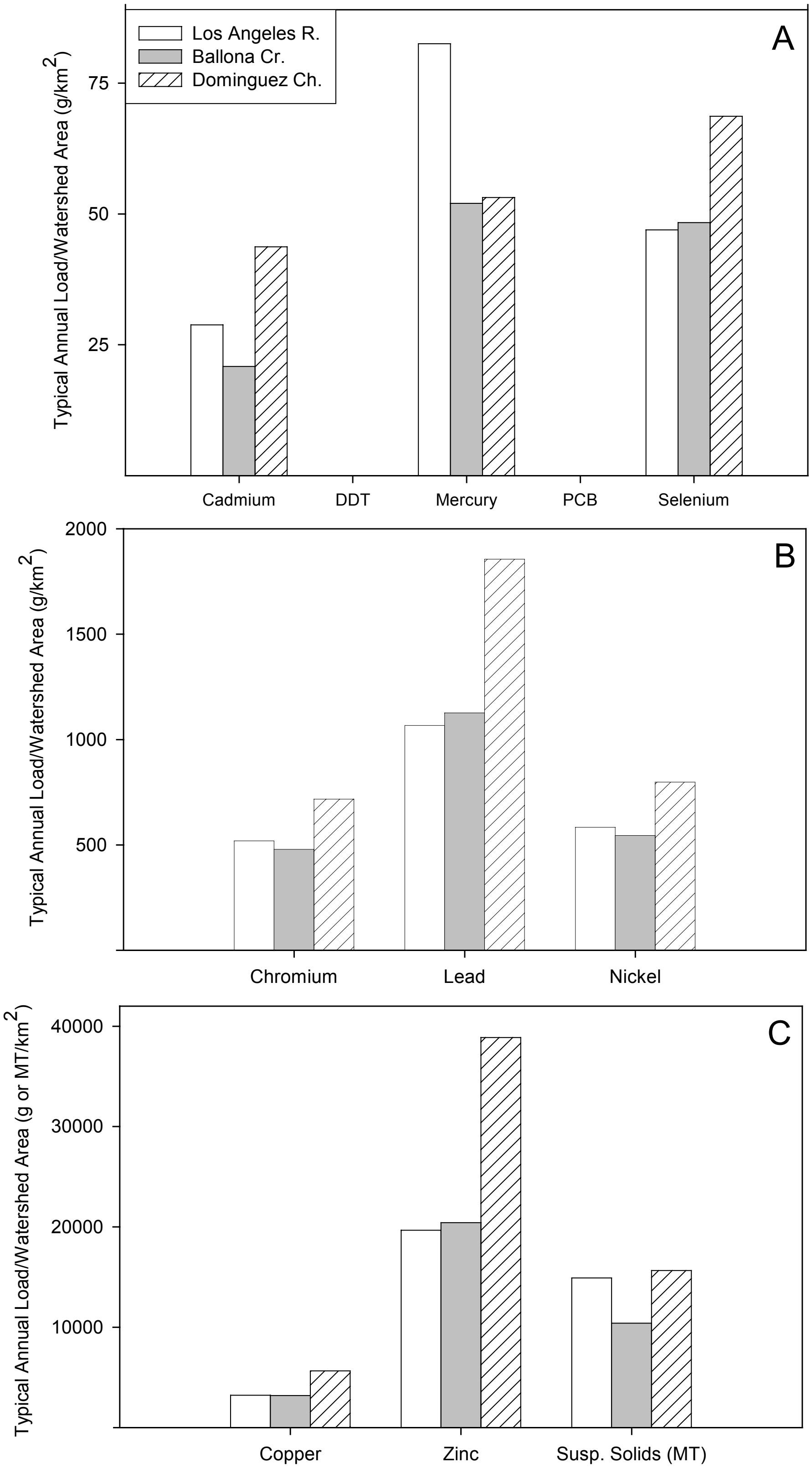

Figure 8. Normalized Typical Annual Wet Weather Loading to the Study Area From Various Watersheds. Bars show 30-year average loading from Los Angeles River, Ballona Creek, and Dominguez Channel, normalized to watershed size. Data are modeled from 30-year average rainfall, land use runoff data, and land use distribution data. Metals data are in kg/km^2 and suspended solids data are in metric tons/km^2. Constituents are grouped in panels A-C based on comparable magnitudes of load.

What land use types are the largest contributors to annual loading?

Pollutants within Los Angeles watersheds are generated from a variety of land use types that collectively contribute to the overall annual load. The distribution of land uses likely affects the magnitude of loading and will influence the range of appropriate management actions. Consequently, understanding the relative loading associated with different land uses is important to developing overall management strategies for contamination in the harbor.

In general, industrial and residential land uses contribute the greatest percent of annual loading to the Los Angeles River (Table 2). These two land uses contribute between 45% (for mercury and chromium) and 75% (for lead and zinc) of the total wet weather load. In contrast, agriculture typically contributes the lowest wet weather load (between 0% and 7% of the total load). There are several notable exceptions to this pattern. For example, open space contributes 53% of the mercury load, which is consistent with patterns seen in other areas where up to 80% of mercury is biogenic, resulting from geologic weathering and aerial deposition (Stein *et al.* 1996). Similarly, 38% of the suspended solids are generated from open space, most likely associated with erosion of natural surfaces.

Table 2. Distribution of Wet Weather Loading from Various Land Uses in the Los Angeles River Watershed. Data are modeled wet weather loads from LADPW based on their routine land use sampling between 1994 and 1999. ND = constituent not detected by LADPW monitoring.

	Agriculture	Commercial	Industrial	Open	Residential	Other	TOTAL (kg)
Cadmium	4.4%	13.6%	41.5%	25.8%	14.0%	0.6%	80
Chromium	7.3%	27.5%	24.1%	19.9%	20.5%	0.6%	1,467
Copper	1.8%	19.8%	42.0%	8.7%	26.9%	0.7%	9,451
DDT	nd	nd	nd	nd	nd	nd	nd
Lead	1.5%	18.7%	39.8%	5.2%	34.1%	0.8%	3,155
Mercury	0.0%	1.2%	13.4%	53.3%	31.7%	0.4%	211
Nickel	5.0%	22.6%	26.0%	19.4%	26.4%	0.6%	1,650
PCB	nd	nd	nd	nd	nd	nd	nd
Selenium	1.0%	15.7%	30.9%	11.7%	39.9%	0.7%	136
Suspended Solids	3.9%	11.0%	24.0%	38.5%	22.1%	0.5%	39,742,143
Zinc	0.4%	20.9%	49.7%	2.8%	25.4%	0.8%	58,977

Relative land-use loading patterns in the watershed result from a combination of differential loading associated with specific land use types and the percent of the watershed that contains each specific land use. To help discern the contribution of intrinsic loading from effects of areal extent of land use, we compared the land use distribution to the distribution of total runoff volume associated with each land use type in several watersheds (Table 3). If the pollutant loading from a specific land use is proportional to its areal extent, the percentages will be the same. In this case, high loadings result primarily from the amount of watershed accounted for by that land use type. If the percent volumetric loading for a particular land use is greater than its percent distribution in the watershed, the loading from that land use likely results from its intrinsic properties. Industrial land uses comprise between 7% and 35% of watershed area, yet contribute between 14% and 52% of volumetric loading. The proportionally higher loading from industrial areas means that high pollutant loading results primarily from intrinsic properties of the industrial land use sites (e.g. high impervious cover, pollutant runoff). In contrast, the areal distribution and volumetric loading of residential land uses are roughly proportional. Therefore, high pollutant loading from residential land uses results primarily from its areal extent in the watershed. Finally, agriculture constitutes a very small percent of total watershed area, and an even smaller percent of volumetric loading. Therefore, low pollutant loading associated with agriculture results primarily from its limited distribution.

Table 3. Volumetric Loading and Areal Distribution of Land Uses for Various Watersheds.

	Agriculture		Commercial		Industrial		Residential		Open		Other	
	area	**Vol**	**Area**	**vol**	**Area**	**Vol**	**area**	**Vol**	**Area**	**Vol**	**area**	**vol**
Los Angeles R.	0.7%	0.3%	7.7%	18.1%	10.1%	24.0%	36.8%	36.4%	44.2%	20.5%	0.4%	0.7%
Ballona Cr.	0.0%	0.0%	15.5%	31.3%	7.0%	14.5%	58.8%	48.1%	17.4%	5.2%	0.6%	0.9%
Dominguez Ch.	1.6%	0.4%	14.9%	21.9%	34.6%	51.5%	41.1%	24.3%	6.9%	1.4%	0.5%	0.5%

The use of these types of models for assessing relative sources within the watershed has at least two major limitations for comparing land use contributions. The first limitation is lack of data for all types of land uses that we may wish to compare. For example, the California Department of Transportation (CalTrans) has been collecting runoff and loading data from freeways for the past several years; however, much of these data are not currently available to the general public. In this model, loading from roads and other transportation structures are imbedded within other land use categories (e.g. roads within a residential area) and are accounted for in the loading estimates for that land use category. Although we can't compare freeways directly, we anticipate that their loading patterns will be similar to those from industrial sites given their impervious cover and intensity of use. A second example of limited data is for Port facilities, which lacks land use cover data, particularly differentiated by the various port activities (conatiner terminal, tank farms, etc.). Provided the land cover data did exist, insufficient wet weather data exist for assessing runoff volumes or water quality representative of an entire storm (Port Districts only collect a single grab sample during a storm event). . However, given that the port constitutes a small portion of the total watershed area draining to San Pedro Bay, its loading will probably not influence the overall distribution of loading shown in Tables 2 and 3. The second major modeling assumption is that everything washed off from a land use is transported through the watershed with equal efficiencies. Although loading from port facilities or regional transportation structures (i.e. Alameda Corridor) are assumed to be small, they are of particular interest due to their proximity to the Bay. However, the current model assumes that pollutants from these areas are transported to San Pedro Bay with the same efficiency as pollutants generated in the San Fernando Valley up to 50 miles upstream. The effect of this assumption has not yet been tested.

CONCLUSIONS AND DATA GAPS

Contaminants may be introduced to harbor sediments through a variety of sources, such as publicly owned treatment works, industrial discharges, and from the watersheds that drain to the harbors. Source control is the most effective long-term strategy to abatement of sediment contamination. This strategy requires an understanding of the patterns and trends of the key sources. Using existing data and modeling, we reached the following general conclusions regarding the sources of contamination to San Pedro Bay and Marina del Rey:

1. Major river watersheds are the largest source of contaminants to the study area.

The vast majority of contaminants are deposited annually from the Los Angeles River, Ballona Creek, and Dominguez Channel watersheds. POTW and industrial discharges constitute a minor fraction of the total annual load to San Pedro Bay.

2. Dry weather discharge may constitute a significant proportion of the total annual contaminant load.

In some years, dry season loading may equal or exceed wet weather loading and constitute the majority of total annual load from the watersheds. This likely results from the arid climate of the region (i.e. some wet seasons do not produce much runoff), combined with consistent (i.e. year-round) dry season discharge, primarily from POTWs and secondarily by storm drains. The magnitude of dry season flow translates to large dry season loading for several contaminants, such as copper, nickel, and zinc. Unfortunately, there is little long term monitoring data for dry season flow, and even less dry season land use runoff data. Consequently, the trends in total annual loading presented in this report likely substantially underestimate the true annual loading to the study area because they typically do not include data from dry weather. Furthermore, it is reasonable to assume that dry season loading has increased with increasing urbanization over time.

3. Long-term (i.e. decadal) trends in annual loading of metals appear consistent, while trends in annual loading of DDTs and PCBs appear to have declined.

Long-term trends in metals loading (with the exception of lead) are influenced primarily by differences in annual precipitation. There does not appear to have been a decrease in metals loading over the last 30 years. In contrast, DDT and PCB loading appear to have declined over the last 30 years. This difference is not surprising given that DDT and PCB use were banned in the mid-1970s, while discharge of metals from watershed-based sources (including aerial deposition has continued relatively unabated.

4. Annual metals loading may vary by up to five orders of magnitude.

Annual loads of most metals are in the $10^3 – 10^5$ kg/year range, with zinc and copper loading typically exceeding loads of other metals, most likely due to their relatively ubiquitous use and distribution. However management strategies should account for typical annual variations of up to five orders of magnitude.

5. The Los Angeles River contributes the greatest overall magnitude of annual load to San Pedro Bay, while Dominguez Channel contributes the greatest proportional annual load.

The Los Angeles River contributes between 85% and 95% of the total annual loading to San Pedro Bay. However, when discharge rates are normalized to watershed size, the Dominguez Channel watershed contributes proportionately greater loading than the Los Angeles River watershed. This proportionately greater loading likely results from the heavily industrialized nature of this watershed. Because Dominguez Channel discharges directly into the Port of Los Angeles (as opposed to the Los Angeles River, which discharges to the edge of the Port of Long Beach), contaminants derived from the Dominguez Channel watershed likely have a greater impact on sediment contamination within the Port of Los Angeles than those discharged from the Los Angeles River.

6. Industrial and residential land uses contribute the greatest percent of annual contaminant loading.

The proportionally higher contribution of contaminants from industrial and residential land uses results from a combination of their areal extent in the watershed and the intrinsically high wash off of pollutants from these land use types. More temporally resolved pollutograph data currently being analyzed by SCCWRP will increase our understanding of the dynamics of buildup, wash off, and loading from specific land uses.

Data Gaps

Our analysis of patterns and trends in contaminant loading was confounded by several key data gaps. Additional data in the following areas would allow for a more complete understanding of contaminant loading to the study area.

Data on loading of PAHs and pesticides

Unfortunately, long-term data sources for loading of PAHs or organophosphate pesticides[6] were not available, so analysis of the contributions and trends for these constituents was not possible. However, preliminary data generated as part of SCCWRP's wet weather "pollutograph study" indicate that more than 7 kg of PAHs can be discharged from the Los Angeles River during a single storm.

Data on dry season loading

Most of the data on total annual loads presented in this report were derived from reported wet weather loading. Since dry season loading can constitute a significant source, these data likely substantially underestimate the true total annual load, especially in relatively dry years. Furthermore, because the dissolved fraction of total metals loading appears to be higher during the dry season than during the wet season, contaminant bioavailability may be higher during the dry season. Additional monitoring and modeling of dry season loading from a range of geographic areas and land use types would greatly improve our understanding of contaminant loading to the harbor.

[6] Storm water samples were analyzed for DDT; however, it was usually not detected.

Data on loading from Dominguez Channel

In general, more comprehensive data is available for the Los Angeles River (and Ballona Creek) than for Dominguez Channel. This particularly true for dry weather data, for which there is none for Dominguez Channel. Given the proportionally large loading from Dominguez Channel directly into the Port of Los Angeles, collection of additional wet and dry weather data would be helpful in understanding loading patterns to the study area.

Data on loading from other potential sources and land use types

Data on other potential sources that directly contribute to San Pedro Bay and Marina del Rey would help improve our estimates of total annual loading. These sources include aerial deposition, vessel anti-fouling paints, direct discharge from ships, and runoff from port facilities. Because these sources discharge directly to the Bay, they may represent a substantial contribution to specific areas of contamination in the study area. In addition, runoff and loading data from transportation structures should also be added to analysis of loading patterns because of the intense vehicle traffic adjacent to the port areas. Preliminary data from all these sources is currently being compiled by various entities. As sufficient data becomes available, it should be included in overall loading estimates.

Contribution of natural loadings

As the various geologic formations that underlay Southern California watersheds weather, they leach certain metals, which may contribute to overall watershed-based loading to the Bay. This was documented by Schiff and Tiefenthaler (2001), who used an iron normalizing technique to assess the magnitude of anthropogenic enrichment of trace metal in suspended sediments in the Santa Ana Watershed and found that nearly all of the nickel and chromium emissions and approximately two-thirds of the copper, lead, and zinc emission, were of natural origin. Determining the contribution of total loading from watersheds that contain a significant amount of undeveloped area, such as the Los Angeles River watershed, will be important to determining appropriate management strategies for watershed-based loading.

More spatially and temporally resolved data on discharge and loading

Most of the reported data on annual loading is extrapolated from a few storms at a few locations. Such extrapolations neglect the effect of intra- and inter storm variability and differences in precipitation and subsequent wash off throughout the local watersheds. More spatially and temporally resolved data will increase our understanding of the dynamics of buildup, wash off, and loading from specific land uses under a variety of precipitation and antecedent moisture conditions. In addition, spatially and temporally resolved data will provide a better understanding of the relationship of storm size on the concentration of contaminants in storm water.

Information on Fate and Transport of Contaminants Within the Study Area

Once contaminants enter the harbor, they may be subject to a variety of transport and transformation processes that can affect the ultimate location and chemical form in which they are deposited to harbor sediments. This in turn will affect the bioavailability of contaminated sediments. Fate and transport models are necessary to fully understand the disposition of watershed-derived contaminants and how they affect different areas of the harbors. Although not the focus of this report, development of estuary and harbor models is an important next step in discerning the relationship between watershed-based loading and sediment contamination.

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APPENDIX A

Table A1: Annual Wet Weather Loads Over Time for Los Angeles River, Ballona Creek, and Dominguez Channel. Data from 1971-72, 1979-80, 1986-88 (SCCWRP), and 1996-2002 (LACDPW). Blank cells indicate no available data.

	Volume (m^3)	Suspended Solids (MT)	Copper (kg)	Lead (kg)	Zinc (kg)	Nickel (kg)	Total DDT (kg)	Total PCB (kg)
Los Angeles River Wet Weather Loads								
1971-72	68,000,000	14,000	9,000	64,000	68,000	5,300	63	180
1979-80	673,000,000	1,350,000	58,000	108,000	646,000	41,000	22	21
1986-87	61,000,000	72,437	8,372	14,682	37,492	2,973	10	19
1987-88	123,900,000	148,011	17,107	29,998	76,609	6,074	20	38
1996-97	82,273,716	24,267	3,629	3,760	16,692			
1997-98	366,346,233	201,394	36,741	94,347	210,012			
1998-99		15,603	1,075		6,078			
1999-00	22,838,049	7,484	286	207	1,012	137		
2000-01	86,132,773	21,024	1,409	879	5,645	700		
2001-02	17,593,254	12,997	514	106	1,022	234		
Ballona Creek Wet Weather Loads								
1971-72	42,000,000	10,000					18	15
1986-87	11,800,000	4,708	1,632	3,354	8,976	462	2	2
1987-88	42,200,000	16,971	5,850	12,093	32,356	1,667	8	7
1996-97	27,383,456	2,971	328	239	2,195			
1997-98	22,572,849	5,987	889	794	8,618			
1998-99	13,198,332	2,649	242	86	1,266			
1999-00	24,775,860	4,214	398	122	1,810	141		
2000-01	29,261,973	4,825	432	179	2,545	128		
2001-02	9,127,819	3,376	191	18	508	54		
Dominguez Channel Wet Weather Loads								
1971-72	10,700,000	10,700					5	4
1986-87								
1987-88								
1996-97		3,964	2,372	880	11,884			
1997-98		18,824	3,769	2,404	43,227			
1998-99		2,867	567	110	6,895			
1999-00	39,313,860	5,715	662	118	7,530	202		
2000-01		4,853	581	96	6,305	123		
2001-02	488,462							

Table A2: Typical Annual Wet Weather Loading to the Study Area From Various Watersheds. Data are modeled from 30-year average rainfall, land use runoff data, and land use distribution data. Metals data are in kg and suspended solids data are in metric tons.

Typical Annual Wet Weather Load (kg)

	Los Angeles River	Dominguez Channel	Ballona Creek
Cadmium	62	8	7
Chromium	1,121	134	162
Copper	6,960	1,056	1,081
Lead	2,304	347	381
Mercury	178	10	18
Nickel	1,260	149	184
Selenium	101	13	16
Susp. Solids (MT)	32,219	2,929	3,522
Zinc	42,479	7,269	6,901

Table A3: Normalized Typical Annual Wet Weather Loading to the Study Area From Various Watersheds. Data are modeled from 30-year average rainfall, land use runoff data, and land use distribution data. Modeled data are normalized by dividing by the total area of each watershed. Metals data are in kg/km^2 and suspended solids data are in metric tons/km^2.

Normalized Annual Wet Weather Load (kg/km^2)

	Los Angeles River	Dominguez Channel	Ballona Creek
Cadmium	29	44	21
Chromium	519	718	479
Copper	3,222	5,646	3,197
Lead	1,067	1,856	1,126
Mercury	83	53	52
Nickel	583	798	544
Selenium	47	69	48
Susp. Solids (MT/km^2)	14,916	15,661	10,419
Zinc	19,666	38,870	20,416