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Identification of subwatershed sources for chlorinated pesticides and polychlorinated biphenyls in the Ballona Creek watershed

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ABSTRACT

Santa Monica Bay forms part of the western border of the greater Los Angeles region. The Ballona Creek watershed is highly urbanized and past studies indicate that Ballona Creek is the largest source for most pollutants to Santa Monica Bay. This study evaluates the contribution of subwatersheds to PCB and chlorinated pesticide loading during wet weather flow. Fifteen storm drains from these subwatersheds were sampled during three storms during the 2005–2006 winter rainy season. A series of grab samples were taken over the duration of the storms. The suspended solids were analyzed for polychlorinated biphenyls (PCBs) and chlorinated pesticides. A geographic information system (GIS) was used to calculate the runoff volume from each subwatershed to estimate pollution mass loading. There was no statistical difference among subswatersheds; however, a disproportionate mass of PCB loading came from site 5, which had no obvious sources. No specific subwatersheds were identified as key sources for chlorinated pesticides. These results may serve as a model for other locations with concerns for historic PCB and chlorinated pesticides loadings.

1. Introduction

Santa Monica forms part of the western border of the greater Los Angeles region. Santa Monica Bay is an important part of the Los Angeles area economy generating approximately US$ 10 billion annually through tourism and recreational activities (NMFS, 1997). Historic inputs of organic pollutants are still affecting pollution levels in Southern California's ocean sediments (Schiff et al., 2000). Pollution inputs into the bay increased until about 1972 when the Clean Water Act was passed (Dojiri et al., 2003). The entire region has separate storm and sanitary sewers, and stormwater runoff receives no treatment other than low flow discharges in the dry season (City of Los Angeles, 2001). Stormwater runoff is the second largest source of pollutants into Santa Monica Bay after treatment plants, depending on the pollutant type (Wong et al., 1997). Southern California has a Mediterranean type climate with an average rainfall of 45 cm/year, where long dry weather periods allow for pollution build up in the watershed, followed by a seasonal first flush (Lee et al., 2004). McPherson et al. (2002) has compared dry and wet weather pollutant loads.

Ballona Creek has been identified as a significant source of organic pollutants entering Santa Monica Bay (Wong et al., 1997). It is a highly urbanized watershed (~65% impervious) and is the largest watershed feeding into Santa Monica Bay. Fig. 1 shows the predominant land use in the watershed is residential. Runoff in the watershed reaches the ocean via a series of storm drains and concrete lined channels.

Pollutants from Ballona Creek may be affecting aquatic communities near the Ballona Creek outflow. Schiff and Bay (2003) showed benthic communities offshore of Ballona Creek were not considered impaired by the Benthic Response Index (BRI); they did not lack pollution sensitive species nor were they predominated by pollution tolerant species. However, the quality of the benthic communities off shore of the Ballona Creek outflow were not as diverse and had more pollution tolerant species than benthic communities in Malibu Creek, which drains a large, mostly undeveloped watershed, also in the Santa Monica Bay watershed. The study showed that the Ballona site had greater concentrations of anthropogenic PCB and DDT as well as PAHs and anthropogenic trace metals than the reference site. This indicates that there may be a correlation between ecosystem health and the metals and organic pollutants coming from Ballona Creek. Another study by Bay et al. (2003) found that interstitial waters from some samples taken at the mouth of Ballona Creek were toxic. The areas immediately impacted by the Ballona Creek discharge are nearer to shore than the DDT-laden sediments associated with the Montrose discharges (Zeng and Venkatesan, 1999); however, the proximity to the two areas heightens local sensitivity to DDT.

Polychlorinated biphenyls (PCBs) are a group of compounds that were manufactured for industrial use. PCBs were sold as varying mixtures of the 209 possible congeners based on average degree of chlorination (Abramawicz, 1990). The production of PCBs was banned in 1977. They are considered to be probable human carcinogens by the United States Environmental Protection Agency (USEPA, 2008) and also affect the immune, endocrine, and reproductive systems (USEPA, 2008). Legacy PCBs are still found in urban runoff in both the United

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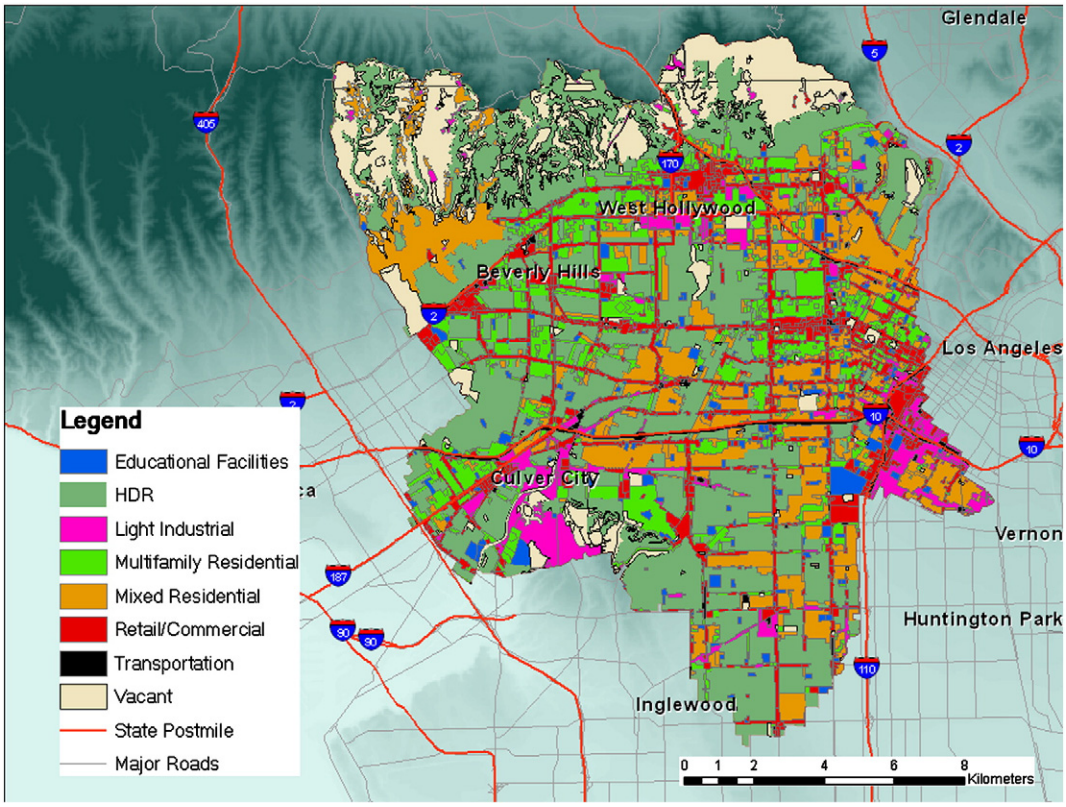

Fig. 1. Land use in the upper Ballona Creek watershed. Land use categorized as HDR is High Density Single Family Residential.

States and Europe, where they have also been banned, and contribute to PCB loading in aquatic communities (Besse et al., 2005; EOA, 2004; Jartun and Pettersen, 2010; Rossi et al., 2004).

Chlorinated pesticides were widely used and manufactured in the United States throughout the mid part of the 20th century. The most famous pesticide in this family is DDT. DDT is a persistent organic pollutant that was eventually banned in the United States in 1972. It is considered a probable human carcinogen by the USEPA and can also affect reproductive systems (USEPA, 2008). Chlordane was sold as a mixture of the two chlordane isomers, mixed with many related compounds. It was used as an insecticide for field crops, until its use was limited to subsurface applications in 1978 (Syracuse Research Corporation, 1990). It was used as a termiticide until it was completely banned in 1988 (Syracuse Research Corporation, 1990). It is a probable human carcinogen and also affects the endocrine, digestive, and nervous systems (USEPA, 2008). Legacy chlorinated pesticides are still found in urban water systems in both the United States and Europe, where they have also been banned, and contribute to PCB loading in aquatic communities (Foster et al., 2003; Leatherbarrow et al., 2005; McKee et al., 2004).

The primary objective of this study was to determine the subwatershed sources of chlorinated pesticides and PCBs to Ballona Creek during wet weather flow. Subwatersheds with high concentrations or high pollution loadings were identified as sources. Subwatershed sources could then be evaluated for early application of Best Management Practices (BMPs).

2. Methods

2.1. Sampling

Fifteen sampling sites were chosen to be representative of the subwatersheds and for accessibility and safety. It was not possible to sample 100% of subwatersheds comprising the entire watershed due to dangerous conditions or accessibility of the storm drain. Fig. 2 shows the sampled sampling sites which are numbered X, 1, 5, 5E, 6, 10, 12E, 12W, 13, 16A, 16B, 20, 22A, 22B, and 22C. Site X was chosen in order to sample the combined runoff of all the upstream subwatersheds. Sites 1 and 5, known as Centinela Creek and the Sepulveda channel, respectively, are downstream of site X, and site 5E is a subwatershed of site 5. Sites 1, 5 and X represent the most western sampling opportunities that are above normal high tide. Total emissions to Santa Monica Bay from the upper Ballona Creek would be the sum of emissions from sites 1, 5 and X.

Storms on 2/27/06, 3/28/06, and 4/4/06 were sampled during the 2005–2006 storm season. The total number of samples collected for the location and storm event depended upon the intensity and duration of the storm, which typically lasted from 5 to 7 h. Grab samples were collected on the half-hour for the first hour and then hourly, for up to 6 h (8 samples total). Site 13 was only sampled during the first storm, after which it was determined to be unsafe for sampling. Site 20 could only be sampled during the first hour of each storm, after which high flows made sampling impossible.

The samples were collected using a metal bucket and stored in 1-gallon or four 1-L acid-washed amber glass bottles with Teflon-lined caps. All sample containers were rinsed three times with the sample immediately before collection. Samples were stored in coolers for transportation to UCLA and stored at 4 °C before processing.

2.2. Analytical procedures

Samples were filtered using pre-washed, pre-weighed 142 mm, 0.7 μm pure glass fiber (no binder) TCLP filters (Whatman Inc., UK) and a Hazardous Waste Pressure Filter System (Millipore, Billerica, MA). Filters were dried in 250 ml glass jars containing calcium chloride over a 24-hour period, based on the method by Capangpangan and Suffet (1996), and then refrigerated at 4 °C until extracted. Filters were reweighed after drying to determine total suspended solids (TSS). Only the suspended solids were analyzed for organic pollutants. The

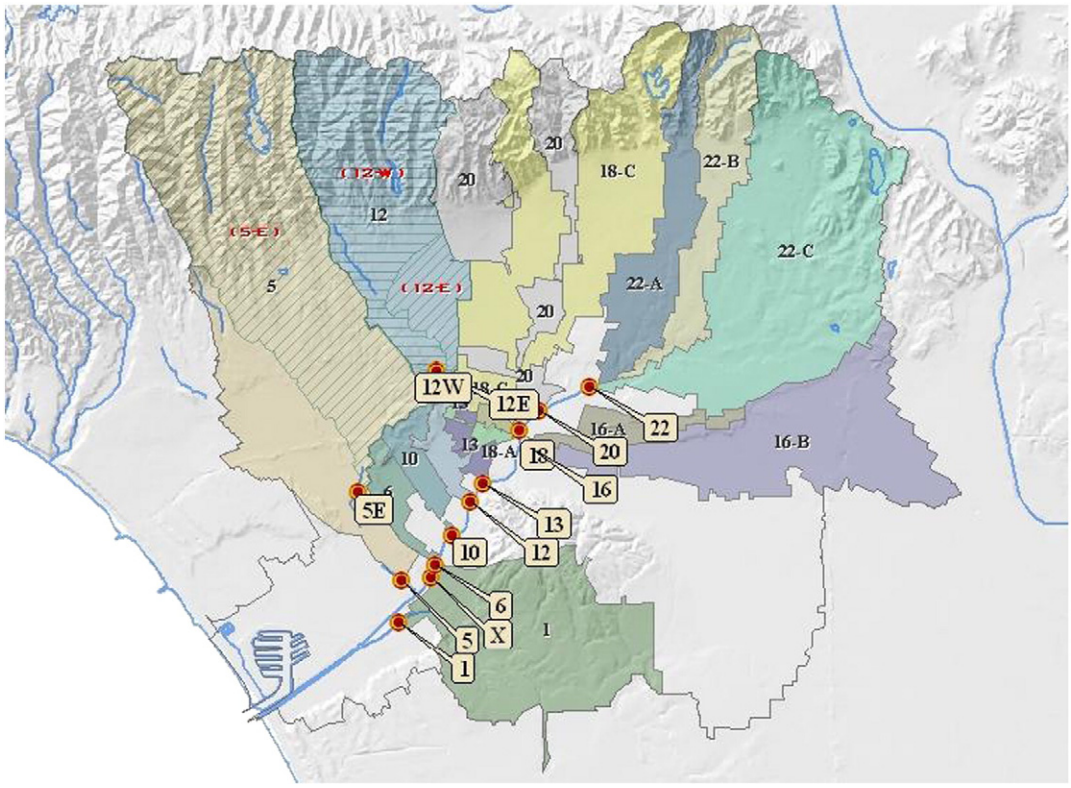

Fig. 2. Sample locations and their subwatersheds.

aqueous portion of the sample was not analyzed because partition coefficients for chlorinated pesticides and PCBs to suspended solids are in the range of 10^3 to 10^7 (Baker et al., 1986; Ding and Wu, 1995), and only a small fraction would exist in the dissolved phase, which was confirmed experimentally in earlier studies. Suspended solids are the main mechanism for transport of PCBs (Hwang and Foster, 2008). PCBs and chlorinated pesticides bound to colloidal particles or soluble DOC (<0.7 μm) may pass through the filter and be missed in the analysis. The suspended solids were analyzed for chlorinated pesticides and PCBs. Microwave extraction of PCBs and chlorinated pesticides, from the suspended solids, was done in accordance with EPA Method 3546 (USEPA, 1996). The solid sample on the filter was extracted into hexane and was processed for analysis for chlorinated pesticides and PCBs. A silica gel cleanup was completed, in accordance with EPA Method 3630C (USEPA, 1996), for samples that had high matrix interference as indicated by initial chromatographic results. Quantification of PCBs and chlorinated pesticides was done using dual GC-ECD in accordance with EPA Methods 8081B and 8082A respectively (USEPA, 1996). Chlorinated pesticide and polycyclic aromatic hydrocarbon (Curren et al., 2008) analysis were given priority and there was sometimes not enough sample remaining for PCB analysis. There were 304 samples analyzed for chlorinated pesticides versus 160 for PCBs.

The chlorinated pesticides studied were aldrin, a-BHC, b-BHC, g-BHC, d-BHC, a-chlordane, b-chlordane, 4,4′-DDD, 4,4′-DDE, 4,4′-DDT, dieldrin, endosulfan I, endosulfan II, endosulfan sulfate, endrin, endrin aldehyde, heptachlor, heptachlor epoxide, and methoxychlor. Method 8082A lists 19 PCB congeners for analysis. In this study BZ 1 was not analyzed, thus only 18 of the 19 congeners were analyzed. The sum of the 18 PCB congeners is reported in this paper as total PCBs. The average concentrations of total PCBs, and chlorinated pesticides, for each storm, were determined for each site.

Equivalent water column concentrations were calculated from TSS concentration and solid phase PCB or pesticide concentrations as follows:

$$C_{runoff} = C_{solid} \times TSS \times 10^3 \quad (1)$$

where C_{runoff} (ng/L) is equivalent concentration of PCBs or pesticides transported by runoff, C_{solid} (μg/kg) is the solid phase concentration of PCBs or pesticides and TSS (mg/L) is the total suspended solids (TSS) concentration of the sample.

2.3. Determining pollution emissions

In order to rank the various subwatersheds, pollution mass emissions from each subwatershed were determined. The model used to calculate the flow volume was a geographic information system (GIS) data set, based upon previous work by Wong et al. (1997). The GIS system was updated to include new coverage for land use from Southern California Association of Governments (SCAG), the subwatersheds' storm drainage system, and elevation data. This data set was used to calculate the total runoff volume for each subwatershed based upon the imperviousness of the various land uses and the measured rainfall for each of the three sampled storms. Two portable rain gauges were used to collect additional rainfall data. Ha and Stenstrom (2008) provide the details of the rainfall and runoff modeling. Runoff flow measurements were not possible due to the inability to locate accurate flow measuring and recording equipment at each sampling site. The calculated flow volumes were multiplied by the average pollutant concentrations at each site to estimate the mass emissions.

3. Results

3.1. Storm events

Storms on 2/27/06, 3/28/06, and 4/4/06 were sampled during the 2005–2006 storm season. Total rainfall in downtown Los Angeles during these three storms was 1.37, 1.62, and 1.44 in. respectively. This rain gauge is at the eastern edge of the watershed. The 2/27/06 storm lasted approximately 7 h and both the 3/28/06 and 4/4/06 storms lasted approximately 5 h. Table 3 list the average flow volume

per storm for the three sampled storms at each site. Despite the higher rain fall during storm 2 at the downtown Los Angeles rain gauge, flow volumes at each site generally decreased with each storm.

3.2. Chlorinated pesticide and PCB concentrations

Chlorinated pesticides detected in at least one sample and comprising the total chlorinated pesticides for this study are: a-BHC, b-BHC, d-BHC, a-chlordane, b-chlordane, 4,4′-DDD, 4,4′-DDE, 4,4′-DDT, dieldrin, endosulfan I, endosulfan II, endrin, and heptachlor. Chlordane and DDT were the pesticides that generally contributed the most to total chlorinated pesticides and were also found at most sites. Aldrin, g-BHC, heptachlor epoxide, endrin, endrin aldehyde, methoxychlor, and endosulfan sulfate were not detected at any sites. Fig. 3 shows that total DDT, chlordane, and total chlorinated pesticide, concentrations varied greatly at a single site between storms and within a storm. Average concentrations for a single storm for all the sampled sites ranged from quantization limits (<1 μg/kg) to 193 μg/kg, 68 μg/kg, and 191 μg/kg or 14.0 ng/L, 6.8 ng/L, and 6.6 ng/L for total chlorinated pesticides, DDT, and chlordane, respectively. ANOVA analysis showed that the subwatersheds were not significantly different from each other for total chlorinated pesticides, total DDT, or chlordane. No subwatershed could be identified as a source for chlorinated pesticides.

DDT was found in the most subwatersheds followed by DDE. DDD was found only at site 20. DDE is the primary breakdown product of

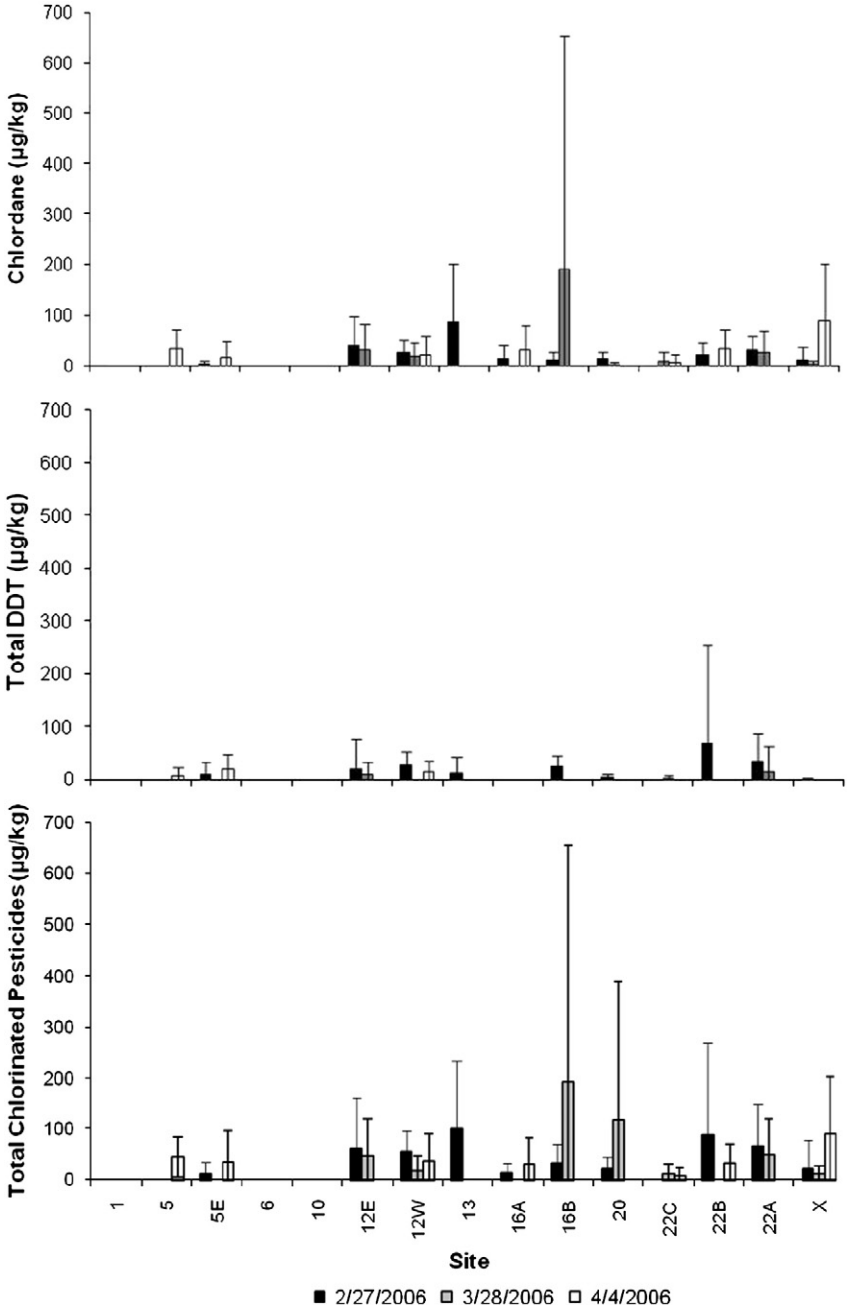

Fig. 3. Chlordane, total DDT, and total chlorinated pesticide concentrations in suspended solids. The ERL and ERM for DDT are 1.58 and 46.1 μg/kg respectively (Long et al., 1995). There is not ERL or ERM for chlordane or total chlorinated pesticides. Chlorinated pesticides detected in at least on sample and comprising the total are: a-BHC, b-BHC, d-BHC, a-chlordane, b-chlordane, 4,4′-DDD, 4,4′-DDE, 4,4′-DDT, dieldrin, endosulfan I, endosulfan II, endrin, and heptachlor.

DDT found in this study. This indicates that photodegradation and microbial dehydrochlorination are primarily responsible for the breakdown of DDT (Aislabie et al., 1997).

Fig. 4 shows the relative total PCB concentrations from each storm drain during each storm. The average PCB concentrations during a single storm ranged from quantization limits (<1 μg/kg) to 119 μg/kg or <0.1 ng/L to 30 ng/L. The maximum concentration observed for any single sample was 339 μg/kg at site 22R or 93.1 ng/L at site 5. As in the case for chlorinated pesticides, ANOVA analysis showed that the drains were not significantly different from each other.

Chlordane and total DDT concentrations in this study were similar to concentrations in other urban and agricultural areas (Table 1). The greatest observed concentration for chlordane is higher than those found in agricultural areas in California (Kratzer, 1999). This may be because chlordane was still used in urban areas for termite control for 10 years after it had been banned as a field crop. Comparing total PCB data to other studies is difficult since there seems to be no consistent number of PCBs that comprise total PCBs and concentrations for individual PCBs are rarely presented. Keeping this in mind, total PCB concentrations for this study are in general agreement with studies done in other areas (Table 2). Particulate phase PCBs found in this study were high, in the range of those found in watersheds with urban, industrial, and military land uses. One watershed with predominantly agricultural use also had high PCB concentrations, ranging from 1 to 124 μg/kg (Foster et al., 2003).

Site X on average had one of the lowest concentrations for total PCBs and total DDT indicating significant dilution. The total chlorinated pesticide concentrations at site X were highest during storm 3. Chlordane was the only pesticide detected at site X during storm 3, both the alpha and gamma isomers were detected. These relatively high concentrations of chlordane at site X indicate an untested storm drain may be contributing to chlordane concentrations at this site. While DDT was low at site X, chlordane was at high concentrations.

3.3. Relative pollution loading

Sites were ranked by the average runoff volume and total pollutant loading (mass per storm) contributed during all three storms (Table 3). Site 5 had the highest loading of PCBs and TSS and one of the highest loads for total chlorinated pesticides. This may have been due to site 5 having the highest flow volume. Sites with higher flow volumes tended to have higher pollution loading, but exceptions can be observed. The existence of exceptions would indicate differences in emissions rates.

To determine if the higher loading was due to high flows or a PCB source, loading per unit area in each of the subwatersheds was compared. Fig. 4 shows the load of PCBs per hectare from each subwatershed for each storm. This was calculated by multiplying the average concentration in the water column (see Section 2.2 for calculation) at the site by the total flow volume for each storm and dividing by the area of the subwatershed for the sampling site. Site 5 was separated into site 5E and site 5W by subtracting the loading from Site 5E from the total load for Site 5. Site 5W has the highest load per hectare for each of the storms, however, ANOVA analysis did not show that the sites were statistically different ($p = 0.15$). Comparing loading from sites 1, 5, and X, the three channels draining the upper

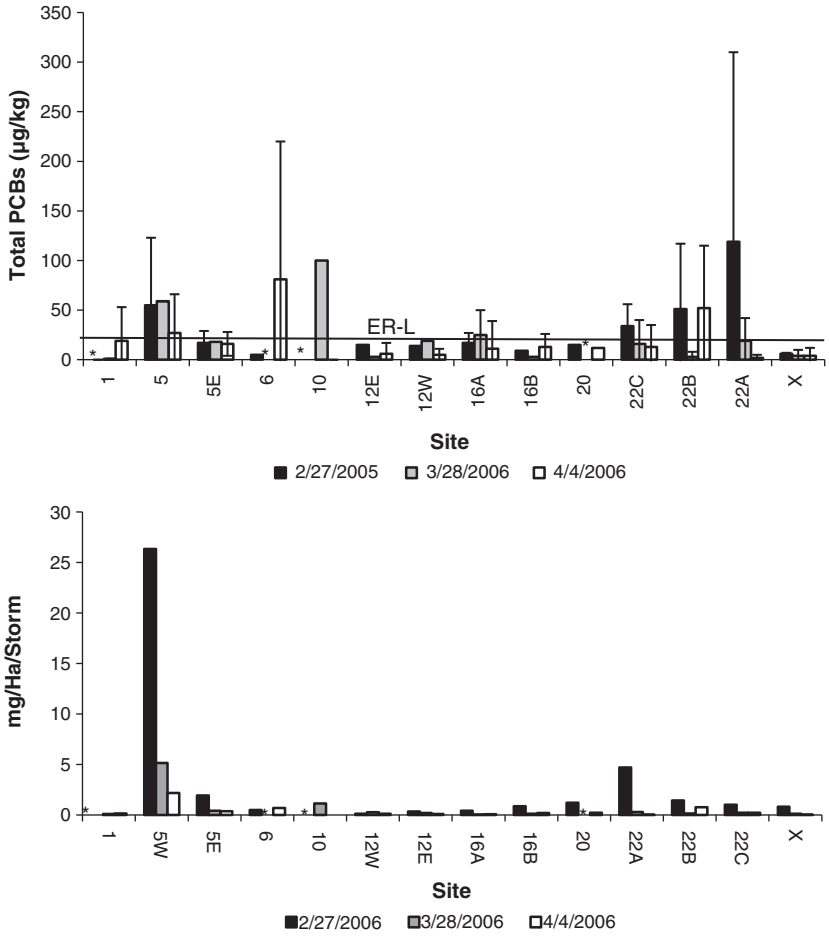

Fig. 4. Average PCB concentration in suspended solids and PCB loading per area per storm for each drain. Error bars are missing when less than three samples were taken during that storm. Sites 1, and 10 were not monitored for the first storm and sites 6 and 20 were not monitored for the second storm (*). The ERL is 22.7 μg/kg (Long et al., 1995).

Table 1
Total DDT and chlordane concentrations compared to other studies.

Region	Type of sample	Weather	Land use	DDT		Chlordane		Reference
				μg/kg	ng/L	μg/kg	ng/L	
Los Angeles, CA	Suspended solids (runoff)	Wet	Urban	ND–70	ND–7[a]	ND–191	ND–7[a]	This study
San Joaquin Valley, CA	Suspended solids (runoff)	Irrigation Wet	Agricultural	71–486 4.7–458		<4–31 1–43		Kratzer, 1999
San Francisco Bay watershed	Water column (river)	Wet	Urban/historical mining		1.7–71		1.6–64	McKee et al., 2004
San Francisco Bay watershed	Water column (river)	Wet	Agricultural/urban		0.24–1.6		0.04–0.18	Leatherbarrow et al., 2005
Chesapeake Bay watershed	Water column (river)	Dry and wet	Urban/suburban		ND (0.09)–7.7		0.21–18.5	Foster et al., 2000
Chesapeake Bay watershed	Water column (river)	Dry and wet	Agricultural/open space/urban		<176			Foster et al., 2003
			Agricultural		<16.4			
Siberia	Water column (river)				0.003–0.016		0.0035–0.0066	Carroll et al., 2008
Southern China	Water column (river)	Sampled monthly	Agricultural/urban		2.85–5.53			Guan et al., 2009
India	Water column (river)	NG	Rural/agricultural/urban		0.87–120		<0.008–2.8	Iwata et al., 1994
Thailand					0.23–2.5		0.18–1.3	
Vietnam					0.29–25		0.045–1	
Malaysia					1.7		2.1	
Indonesia					0.22–0.27		0.071–0.26	
Solomon Islands					0.01–2.7		<0.0018–0.14	
Japan					0.0011–0.0027		0.063–0.15	
Taiwan					0.0007–0.012		0.012–0.11	
Australia					<0.0001–0.033		<0.006–1.2	

NG: not given; ND: non-detect.
[a] Calculated from suspended solids concentration.

Ballona Creek watershed, shows approximately 50–70% of PCB loading came from site 5, while approximately 20% of the flow came from site 5. With data from only three storms, our study may not be powerful enough to identify 5W as a source. However, the disproportionate loading of PCBs from site 5 may indicate a potential source of PCBs and merits further investigation. A similar analysis was done for total chlorinated pesticides; however, no subwatershed had a consistently high load per unit area for all three storms.

The cumulative loading of sites upstream from X was compared to the loading at X to determine if one of the untested drains could be a source for PCBs or chlorinated pesticides. PCB loading at X was approximately equal to the loading from all tested upstream sites; upstream sites and site X had an average load per storm of approximately 8 g. However, chlorinated pesticide loading at site X was approximate twice that of the loading from tested upstream sites; approximately 20 g at site X versus approximately 10 g from upstream sites for each storm. This indicates the untested subwatersheds were not important sources of PCBs, but were important contributors to chlorinated pesticide loading.

3.4. Environmental toxicity

3.4.1. NOAA sediment quality guidelines

Total PCB and total DDT concentrations in the suspended solids were compared to National Oceanic and Atmospheric Administration (NOAA) sediment quality guidelines for marine and estuarine sediments. Sediment quality guidelines have not been determined for chlorinated pesticides other than DDT. NOAA has set the effects range-low (ERL) at the tenth percentile of the effects data distribution and the effects range-median (ERM) at the fiftieth percentile (Long et al., 1995). Sediments with concentrations below the ERL are expected to have toxic effects less than 25% of the time, while concentrations above the ERM are expected to have toxic effects more than 75% of the time (Long et al., 1995). These guidelines were chosen as point of comparison because suspended solids in Ballona Creek may eventually settle in Santa Monica Bay. Besse et al. (2005), showed that PCB concentrations in the suspended solids are enriched compared to sediment concentrations, possibly due to smaller grain size or higher organic carbon content; concentrations in Santa Monica Bay sediments would be expected to be lower than those in suspended sediments. ERL and ERM values are meant to be used as an informal screening tool and more formal toxicity and biological testing would be needed to obtain a better understanding of potential environmental impacts (Long et al., 1995).

The ERL and ERM were compared to total DDT concentrations and total PCB concentrations in Figs. 3 and 4, respectively. The ERL for DDT and PCBs are 1.58 μg/kg and 22.7 μg/kg, respectively (Long et al., 1995). Of the 15 sites analyzed for total DDT, the average concentration at 11 sites exceeded the ERL, for at least one storm (Fig. 4). The average concentration of DDT at site 22B exceeded the ERM, 46.1 μg/kg (Long et al., 1995), during storm 1. The average concentration at site X was below the ERL for all three storms indicating that BMPs targeting DDT are not needed at site X. For total PCBs, average concentrations at sites 6, 10, 16A, 22A, and 22C exceeded the ERL during one storm, and at site 22B exceeded the ERL during two storms; however, the average concentration at site X was below the ERL for all three storms. The average concentration of PCBs at site 5 exceeded the ERL during all three storms, and no sites exceeded the ERM (Fig. 4). Out of 160 samples analyzed for PCBs, 37 exceed the ERL and 2 exceeded the ERM. Average PCB concentrations at each site were always below the ERM. Of 304 samples analyzed for DDT, 31 exceeded the ERL and 15 exceeded the ERM. The average DDT concentration at site 22B exceeded the ERM for storm 1.

3.4.2. California Ocean Plan

Pollutant concentrations were converted from the concentration in the suspended solids (μg/kg) to the water column concentration (ng/L) by multiplying the suspended solids concentration by the concentration of the pollutant in the suspended solids (see Section 2.2). The concentration of the pollutant in the water column at sites 1,

Table 2
PCB concentrations compared to other studies.

Region	Type of sample	Number of PCBs analyzed	Weather	Land use	Concentration range		Reference
					µg/kg	ng/L	
Los Angeles, CA	*Suspended solids (runoff)*	*18*	*Wet*	*Urban*	*ND–119*	*ND–34*[a]	*This study*
Fort Worth, TX	Suspended solids (runoff)	27	Wet	Residential	0.5–14.8		Besse et al., 2005
				Air Force	81.3–166		
Chesapeake Bay watershed	Suspended solids (river)	75	Dry and wet	Agricultural/open space/urban	Feb-62		Foster et al., 2003
				Agricultural	1–124		
San Francisco Bay watershed	Embedded sediment	54	Dry (storm drains)	Urban	2.0–53 (16,810[b])		EOA, 2004
Norway	Embedded sediment	7	Dry (storm drains)	Urban	<3		Jartun and Pettersen, 2010
Norway	Embedded sediment	7	Dry (storm drains)	Urban	20–54		Cornelissen et al., 2008
Hudson River	Water column (river)	Arochlors 1221, 1016, 1254		General Electric plants major source of PCBs		130–540	Sloan et al., 1983
Chesapeake Bay watershed	Water column (river)	85	Dry and Wet	Urban/suburban		0.20–28.9	Foster et al., 2000
Chesapeake Bay watershed	Water column (tidal river)	85	Dry	Urban/suburban/	31.0–755	0.91–11.8	Hwang and Foster, 2008
			Wet	former Navy		9.82–211	
San Francisco Bay watershed	Water column (river)	69	Wet	Urban/historical mining		3.4–90	McKee et al., 2004
San Francisco Bay watershed	Water column (river)	40	Wet	Agricultural/urban		0.2–6.7	Leatherbarrow et al., 2005
England	Water column (river)	11	Dry and wet	Urban	53.8	0.53–3.18	Meharg et al., 2003
Switzerland	Water column (runoff)	12	Wet	Industrial/residential		20–60	Rossi et al., 2004
Siberia	Water column (river)	10				0.059–0.078	Carroll et al., 2008
Southern China	Water column (river)	20	Sampled monthly	Agricultural/urban		0.12–1.47	Guan et al., 2009
India	Water column (river)	NG	NG	Rural/agricultural/		0.34–48	Iwata et al., 1994
Thailand				urban		<0.24–4.4	
Vietnam						0.57–8	
Malaysia						0.45	
Indonesia						0.38–2.1	
Solomon Islands						<0.05–1.1	
Japan						0.35–0.74	
Taiwan						0.085–2.1	
Australia						<0.05–2.2	

NG: Not given.
ND: Not detected.
[a] Calculated from suspended solids concentration.
[b] Found during previous study.

5, and X were compared to the water quality guidelines of the California Ocean Plan (COP), since these are the three channels that drain the upper Ballona Creek watershed (Table 4). The 1997 plan specifies a total DDT concentration upper limit of 0.17 ng/L and 0.023 ng/L for chlordane (CEPA, 2001). The plan also specifies an upper limit for total PCBs of 0.019 ng/L (CEPA, 2001). Site 5 was above the COP limiting concentration for DDT. Sites 5 and X were above the COP limiting concentration for chlordane. All sites were above the COP limiting concentration for total PCBs. Dilution will occur when the stormwater reaches the ocean, and the extent of this dilution will affect the impact the pollutant will have on the environment. Washburn et al. (2003) evaluated the dispersion of stormwater plume from Ballona Creek. Their study showed that stormwater plumes from Ballona Creek could be identified from salinity profiles as much as 4 km off-shore.

Bay et al. (2003) showed that stormwater plumes from Ballona Creek were toxic whenever the storm water dilution was less than tenfold; however, Bay et al. (2003) found this toxicity to be primarily attributed to zinc, not organic pollutants. Toxicity due to these hydrophobic pollutants is more likely to be found in sediments than in the water column. High water column concentrations are likely to be short lived at this site; therefore sediment concentrations are more important to consider than water column concentrations when evaluating environmental impacts for this site.

Table 3
Ranking of sites by runoff volume and pollutant mass emission. Average mass emission or flow volume for the three storms is given in parenthesis.

Volume (10^3 m^3)	TSS (10^3 kg)	Chlorinated pesticides (g)	DDT (g)	Chlordane (g)	PCB (g)
5 (1220)	5 (303)	16B (4.3)	16B (1.6)	16B (2.0)	5 (21.5)
22C (1000)	16B (174)	5 (3.2)	12W (1.6)	5 (1.8)	5E (4.1)
5E (850)	5E (158)	5E (2.0)	5E (1.2)	12W (1.8)	22C (2.0)
16B (670)	22C (126)	20 (1.5)	5 (0.5)	20 (0.9)	22A (1.9)
1 (500)	12W (95)	12W (1.3)	22A (0.5)	5E (0.8)	20 (1.2)
12W (430)	1 (60)	22A (1.1)	20 (0.3)	22A (0.5)	16B (1.0)
20 (350)	20 (57)	12E (0.9)	22B (0.3)	22B (0.4)	22B (0.9)
22A (260)	22B (29)	22B (0.7)	22C (0.1)	13 (0.3)	12W (0.4)
22B (220)	22A (22)	22C (0.5)	12E (0.1)	12E (0.2)	1 (0.3)
12E (110)	12E (11)	13 (0.3)	13 (0.02)	22C (0.2)	10 (0.2)
16A (70)	6 (10)	16A (0.1)	16A (0)	16A (0.1)	6 (0.2)
10 (60)	13 (8)	10 (0)	10 (0)	10 (0)	12E (0.1)
6 (60)	16A (6)	6 (0)	6 (0)	6 (0)	16A (0.1)
13 (40)	10 (5)	1 (0)	1 (0)	1 (0)	

3.4.3. PCB source identification

Aroclors are a mixture of PCBs with varying amounts of the different congeners. While the exact composition of congeners in an

Table 4
California Oceans Plan (COP) limiting concentration (CEPA, 2001) compared to average at Sites 1, 5, and X.

	COP (ng/L)	Site X (ng/L)	Site 5 (ng/L)	Site 1 (ng/L)
Total DDT	0.17	0.06	0.4	ND
Chlordane	0.023	2.4	1.5	ND
Total PCB	0.019	1.3	16.07	0.74

Table 5
PCB congeners detected at site 5 for each of the three storms.

BZ	Aroclor							Storm		
	1016	1221	1232	1242	1248	1254	1260	1	2	3
5	x	x	x	x	x					
31	x		x	x	x	x				x
44			x	x	x	x	x			
66				x		x	x	x		
110						x		x		x
153							x	x		x
138							x	x		x
180							x	x	x	x
170							x		x	

Aroclor may vary from batch to batch, certain congeners are known to be important components of a given Aroclor. PCB congeners found in this study were compared to common congeners found in various Aroclors as described in the EPA Method 8082A (USEPA, 1996). The small number of PCB congeners evaluated in this study, 18 congeners, is best suited for screening large numbers of samples to identify potential problem areas (Morrison and Murphy, 2006), which was our primary objective. Ideally at least 20 congeners should be analyzed to identify source by PCB composition (Morrison and Murphy, 2006).

Since site 5 was identified as a potential source of PCBs, source identification was done only in this subwatershed. Table 5 shows that higher substituted congeners are more often found in the samples. Comparisons in Table 5 shows Aroclors 1254 and 1260 are the most likely the source Aroclors. Aroclors 1254 and 1260 were commonly used in transformer askarels (Morrison and Murphy, 2006). However, both Aroclors had many other uses and comprised approximately 27% of PCBs sold in the USA by weight (Morrison and Murphy, 2006). Aircraft manufacturing was an important part of the Southern California economy and historic sites of production are potential sources of PCBs. There are many potential sources and a more in-depth look at land use history and further monitoring studies in the western portion of site 5 would be needed to identify a source of PCBs.

4. Conclusions

PCBs and chlorinated pesticides were analyzed in stormwater runoff from 15 subwatersheds in the Ballona Creek Watershed, a highly urbanized 160 km^2 section of west Los Angeles, California. The PCBs and chlorinated pesticides found in this study were generally in the range found in other studies. Average concentrations of PCB and total DDT at sites 1 and X were below NOAA screening concentrations, indicating they are unlikely to cause toxic effects. Site 5 exceeded the ERL (effects range low) for PCBs for all three storms sampled. Approximately 25% of the PCB samples exceeded the ERL but only 2 samples exceed the ERM (effects range medium). Average PCB concentrations at each site were always below the ERM. Only 10% of the DDT samples exceeded the ERL and 5% exceeded the ERM. Only one site for one storm had an average concentration that exceeded the ERM, but 11 sites exceeded the ERL for at least one storm event.

There was no statistical difference among subswatersheds; however, a disproportionate mass of PCB loading came from site 5, which had no obvious sources. Further studies are needed to determine if there is an upstream source of the PCBs at site 5. No subwatershed sources for chlorinated pesticides could be determined. Subwatersheds that contributed the highest loading of chlorinated pesticides also tended to have the highest flow volumes. However, higher loading at site X than from contributing sites indicates that one of the untested drains may be a source for chlorinated pesticides other than DDT.

The cited literature suggests that our results will likely be applicable to other urban areas with legacy uses of PCBs and chlorinated pesticides. Further reductions in emissions of these pollutants can only be achieved through reductions in suspended solids discharge in stormwaters. These same urban areas may require reductions in metals emissions, and a good way of achieving reductions is also through reducing suspended solids. It will be more advantages to justify and construct technologies to reduce metals and other pollutants associated with suspended solids, which will also reduce PCB and chlorinated pesticide emissions. This may be a better way of justifying BMP construction.

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