Effect of antecedent dry periods on the accumulation of potential pollutants on parking lot surfaces using simulated rainfall

Liesl L. Tiefenthaler, Kenneth C. Schiff, Steven M. Bay, and Darrin J. Greenstein

ABSTRACT - The relationship between antecedent rainfall and pollutant build-up is difficult to quantify, particularly in arid environments, due to the inherent unpredictability and natural variability in rainfall. To overcome this variability, a rainfall simulator was constructed to mimic storm events under controlled conditions. Simulated storm events at monthly intervals were used to measure increasing contaminant concentrations in parking lot runoff over a three-month dry period. Secondarily, the rainfall simulator was used to measure changes in runoff water quality from parking lot surfaces with varying traffic use and maintenance practices. Virtually all of the accumulation occurred within one month for total suspended solids, total trace metals, and dissolved trace metals. Mean concentrations in runoff from simulated storm events in subsequent sampling months remained steady relative to Month 1. Factors such as traffic use and maintenance did not affect the monthly accumulation of pollutants in runoff during the simulated storm events.

INTRODUCTION

Seasonal flushing, where pollutant concentrations and mass emissions in urban runoff increase after long dry periods of antecedent rainfall, is a common assumption among stormwater quality managers, but has proven difficult to quantify. Leecaster *et al.* (2001) found that early-season storms typically had higher concentrations than storms later in the storm season. Similarly, Bay *et al.* (1997) found that toxic responses of marine organisms increased in the first storm of the wet season compared to toxicity measured in subsequent storm events. However, neither study was able to quantify or predict the relationship between antecedent rainfall and the build-up of pollutants that led to increased concentration, mass, or toxicity.

PICTURE

The difficulty in quantifying the relationship between antecedent rainfall and pollutant accumulation is due to the inherent unpredictability in timing and natural variability in rainfall characteristics. Rainfall characteristics such as intensity, duration, and quantity are confounding factors in defining the pollutant build-up over varying periods of antecedent dry weather. For example, differences in rainfall intensity and duration led to 2-fold to 10-fold differences in runoff concentrations among storms of similar intensity and duration (Tiefenthaler *et al.* in press). The difficulty in defining rainfall:pollutant accumulation relationships is compounded in arid climates where dry spells of four to six months are routine and rainfall intensity and duration typically covary (Herricks 1995).

The goal of this study was to evaluate the effects of increasing antecedent conditions and pollutant concentrations in surface runoff. The natural variability inherent to rainfall was eliminated by testing accumulation using a rainfall simulator that consistently replicated rainfall duration and intensity, enabling controlled evaluations of rainfall frequency. The rainfall simulator was deployed in arid southern California to determine whether extended antecedent dry periods resulted in greater accumulation of pollutants.

Pollutant accumulation was examined using the rainfall simulator on highly impervious parking lot surfaces. Parking lot surfaces were selected for two reasons. First, increasing impervious surface area is related to degraded water quality in urbanizing areas (Schueler 1997), and parking lots are considered critical source areas for urban land uses (Bannerman *et al.* (1993). Second, traffic use and parking lot maintenance are potential contributors to the build-up of runoff constituents. Therefore, a secondary objective was to measure the accumulation of constituents in simulated rainfall from high-use versus low-use parking lots, as well as from parking lots that were regularly maintained versus those that were not maintained.

METHODS

Rainfall Simulator

In this study, parking lot runoff was generated using rainfall simulators (spray rigs) designed to duplicate median-sized rainfall intensities in the southern California region. Each spray rig was comprised of polyvinyl chloride (PVC) pipes and equipped with its own pressure gauge, flow meter, control valve, and fixed-rate Rainbird™ rotating polyurethane spray head (Figure 1). The spray rig, at 45/36 pounds per square inch (psi) and 5.0 liters per minute (L/min) flow rate, produced a 3.8 m radius semicircle with an intensity of 12.7 mm/h. Measurements of rainfall intensity within the semicircle at nine evenly spaced locations varied by less than 20%, and mean intensities among simulations varied by less than 10%.

Each rainfall simulation lasted 20 minutes and generated an approximate runoff volume of 26.4 L. The runoff was collected continuously during each simulated event using a vacuum system that transferred the runoff into a 55-gallon plastic barrel. At the end of each simulation, the runoff collected in each barrel was stirred vigorously and subsamples for chemical analysis were taken. The source water for the rainfall simulators was passed through a portable filtration system comprised of filters and activated carbon to remove potential confounding factors. All source water blank samples and rainfall simulator blank samples were nondetectable for our measured constituents.

Accumulation Experiment

To assess existing conditions at the parking lot, a simulated rainfall event was collected at the beginning of the study. Immediately following this event, the entirety of the parking lot was cleaned using a professional-grade, commercially available cold water pressure washing system to ensure that all potential sampling surfaces started at similar levels of accumulation. Immediately following the pressure washing, a simulated rainfall event was collected to determine initial conditions prior to accumulation. Samples were then collected at monthly time intervals for three months. There was no measurable rainfall during the entire test period, which lasted from June to September, 2001. For each time period, three replicate sampling sites within the parking lot were selected at random. Each site consisted of approximately two parking stalls and no stall was sampled twice.

The parking lot, located in Long Beach, California, had a capacity of 100 cars with dimensions of approximately 8 m by 76 m and a 4% grade. The site, which was constructed of 100% asphalt, operated seven days per week with five days at full capacity.

Maintenance and Traffic Intensity

Similar to the accumulation experiment, a randomized factorial design was used to measure the effects of traffic intensity and parking lot mainte-

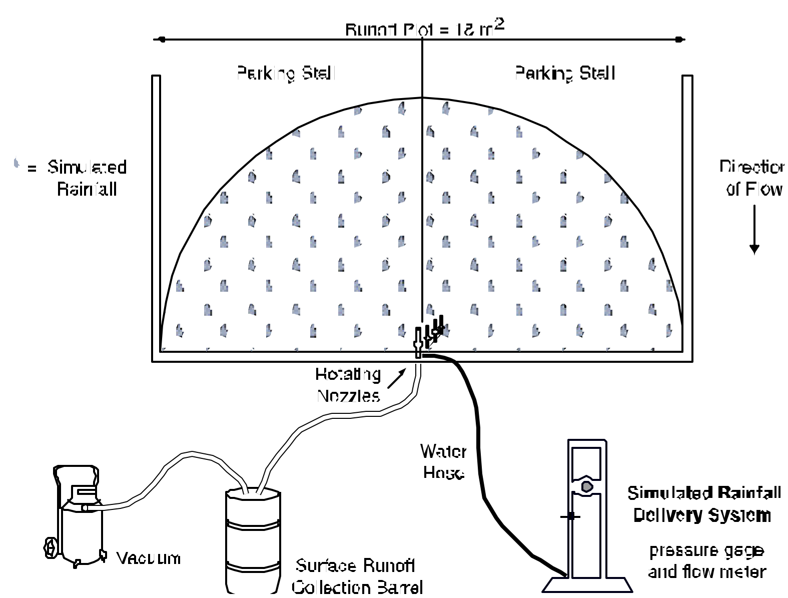

FIGURE 1. A schematic diagram illustrating (a) the simulated rainfall delivery and (b) the water collection system used for assessing the effects of rainfall on surface runoff.

nance. Traffic intensity was defined as either low use (1 car/4 h) or high use (5 or more cars/h). Parking lot maintenance included street sweeping, which was conducted on a weekly basis. Cleaning consisted of an individual using a backpack blower and/or broom to move visible loose debris and surface dirt into the path of a power vacuum truck for collection and removal. Three replicates of each treatment type were collected during each monthly sampling interval.

Analytical Chemistry

Total suspended solids were analyzed by filtering a 10 to 100 mL aliquot of stormwater through a tared 1.2 mm (micron) Whatman GF/C filter (EPA Method 160.2). The filters plus solids were dried at 60°C for 24 h, cooled, and weighed.

Samples for total and dissolved trace metal analysis were prepared by strong acid digestion using HNO_3 and analyzed using EPA Method 200.8, EPA Methods 236.1 and 236.2, and by EPA Modified Method 245.1 (U.S. EPA 1991). Dissolved metals were measured similar to total metals, except that the dissolved metals were prepared by passing water samples through a 0.45 µm filter prior to extraction. Inductively coupled plasma-mass spectroscopy (ICP-MS) was used to determine concentrations of trace metal inorganic constituents (aluminum, antimony, arsenic, beryllium, cadmium, chromium, copper, iron, lead, mercury, nickel, selenium, silver, and zinc).

Twenty-six polycyclic aromatic hydrocarbons (PAHs) were extracted, isolated, and analyzed using EPA Method 8270C (U.S. EPA 1991). The PAHs were separated, identified, and quantified by capillary gas chromatography (GC) coupled to mass spectrometry (MS). Total PAHs (ΣPAH) was computed as the sum of the 26 individual PAH compounds.

RESULTS

Pollutant Accumulation

Concentration of all the measured constituents in parking lot runoff increased after one month of accumulation, with the exception of total PAHs (Table 1). For example, mean suspended solids concentrations increased from 29.2 mg/L to 51.8 mg/L (59%) during this time period. After one month of accumulation, total zinc increased by 182%, the most of any trace metal measured. Similarly, the greatest accumulation by any dissolved trace metal was zinc, increasing by 276% after one month. In contrast, mean total PAH concentrations were highest prior to accumulation and subsequently decreased 20% after one month.

Pollutants ceased to accumulate after one month (Table 1). Mean concentrations in subsequent sampling months either remained steady or decreased relative to Month 1. For example, suspended solids concentrations decreased from 52 mg/L accumulation to 47 mg/L in Month 1, then 41 mg/L in months 2 and 3, respectively. Total zinc concentrations in parking lot surface runoff from Month 1 were approximately two-fold to three-fold greater than the concentrations in runoff from other time periods. Monthly PAH concentrations decreased to a minimum of 52.9 ng/L, one-half the concentration at the beginning of the accumulation experiment.

Parking lot runoff concentrations responded to pressure washing, decreasing after this relatively rigorous cleaning (Table 1). For example, average TSS concentrations were 26% lower after pressure washing compared to TSS concentrations prior to pressure washing. All of the total and dissolved trace metals also had lower concentrations after the sites were cleaned, with the exception of cadmium and chromium. Mean total PAH concentrations decreased by 14% after cleaning.

Parking Lot Usage

Changes in parking lot vehicular use had little influence on surface runoff contaminant concentrations (Table 2). Only 8 of 18 contaminants displayed higher runoff concentrations from the high-use stations compared to the low-use stations. However, no significantly different concentrations were found for any of the constituents among the treatments measured for parking lot runoff.

Mean contaminant concentrations followed similar temporal trends as observed in the accumulation study (Figure 2). Mean TSS concentrations in parking lot runoff increased after one month of accumulation, then remained relatively steady for Months 2 and 3. Likewise, mean zinc concentrations in runoff from both low-use and high-use parking lots increased after one month of accumulation, then decreased in Months 2 and 3. Regardless of the constituent, the trend in accumulation, and the overall magnitude of accumulation, were not significantly different among high-use and low-use parking lot sites.

Table 1. Comparison of constituent accumulation over time. Values given are means of all treatments and their standard deviations.

	Washoff Events				
	15-Jul-00	15-Jul-00	12-Aug-00	9-Sep-00	7-Oct-00
	Preclean	Time 0	Month 1	Month 2	Month 3
Parameter	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Suspended Solids (mg/L)	50 (25.4)	29.2 (11.7)	51.8 (14.1)	46.7 (37.2)	41.0 (10.8)
Total Metals					
Aluminum (µg/L)	315 (134.4)	250 (82)	533.3 (119.2)	423.3 (100.7)	421.7 (97)
Cadmium (µg/L)	0.7 (0.9)	1.3 (1.4)	2.5 (1.4)	0.9 (1.0)	0.0 (0)
Chromium (µg/L)	1.2 (1.6)	1.4 (1.1)	3.6 (0.5)	2.3 (0.5)	3.2 (0.4)
Copper (µg/L)	37.5 (13.4)	32.0 (9.2)	40.3 (7.2)	28.7 (6.8)	19.2 (3.2)
Iron (µg/L)	835 (7.1)	546.7 (154.5)	810.0 (174.4)	496.7 (130.1)	485.0 (97.4)
Lead (µg/L)	20 (11.3)	35.0 (9.2)	41.8 (10.6)	19.5 (8.5)	10.9 (2.2)
Mercury (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Nickel (µg/L)	16.3 (9.5)	14.2 (5.8)	20.7 (2.4)	16.5 (4.5)	9.2 (1.9)
Silver (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Zinc (µg/L)	530 (169.7)	220.0 (85.1)	620.0 (60.4)	395.0 (107.1)	230 (34.9)
Total PAHs (ng/L)	140 (14.1)	105 (46.0)	82.4 (33.7)	52.9 (10.7)	53.3 (6.8)
Dissolved Metals					
Aluminum (µg/L)	180 (70.7)	46.4 (27)	131.7 (62)	71 (33.4)	63.7 (4.2)
Cadmium (µg/L)	0 (0)	0.9 (1.0)	1.3 (1.2)	0.6 (0.8)	0.0 (0.0)
Chromium (µg/L)	0.9 (1.3)	1.0 (0.9)	2.3 (1.1)	1.5 (0.4)	1.9 (0.1)
Copper (µg/L)	32 (11.3)	27.3 (9.3)	28.5 (13.4)	19.3 (4.1)	13.5 (2.1)
Iron (µg/L)	285 (77.8)	263.3 (77.3)	286.7 (140.0)	118.7 (39.0)	66.2 (11.0)
Lead (µg/L)	9.7 (4.7)	32.3 (9.0)	22.8 (14.0)	10.9 (7.2)	3.6 (1.5)
Mercury (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Nickel (µg/L)	14.5 (7.8)	12.9 (5.8)	16.2 (7.7)	11.1 (2.6)	7.5 (1.1)
Silver (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Zinc (µg/L)	405 (176.8)	200 (78.9)	553.3 (50.5)	270.0 (89.4)	158.3 (18.4)

Maintenance

Changes in parking lot maintenance had little influence on surface runoff contaminant concentrations (Table 2). Only 3 of 18 contaminants actually had lower runoff concentrations from the maintained parking lot compared to the non-maintained parking lot.

Mean contaminant concentrations in runoff from maintained and non-maintained parking lots followed similar temporal trends as observed in the accumulation study (Figure 3). Mean TSS concentrations in runoff from both maintained and non-maintained parking lots increased after one month of accumulation, then remained relatively steady for Months 2 and 3. Likewise, mean zinc concentrations in runoff from maintained and non-maintained parking lots increased after one month of accumulation, then decreased in Months 2 and 3. Regardless of the constituent, the trend in accumulation, and the overall magnitude of accumulation, were not significantly different among high-use and low-use parking lot sites.

DISCUSSION

Instead of parking lot concentrations consistently increasing over an entire summer, the parking lot we studied in southern California reached a maximum accumulation of pollutants within 28 d. Pollutants in parking lot runoff then leveled off, or decreased, for the ensuing two months. Similarly, Pitt and Sutherland (1982) estimated that the total mass of pollutants that can accumulate on street surfaces is limited, requiring approximately two to three weeks to reach maximum levels. The maximum accumulation rate may be a reflection of physical processes, such as wind or turbulence from traffic, that can limit the

Table 2. Comparison of parking lot runoff concentrations among parking lot usage and maintenance practices. Time periods were pooled and means with their standard deviations are reported.

	Pooled Time Periods (T1-T3)			
	Use		Maintained	
	Low	High	Yes	No
Parameter	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Suspended Solids (mg/L)	44.9 (19.3)	46.4 (27)	59.7 (23.4)	36.7 (19.4)
Total Metals				
Aluminum (µg/L)	506.7 (135.9)	412.2 (83.2)	546.7 (138.4)	415.8 (84.8)
Cadmium (µg/L)	0.9 (1.5)	1.4 (1.3)	1.1 (1.2)	1.1 (1.4)
Chromium (µg/L)	3.1 (0.6)	3 (0.8)	3.4 (0.8)	2.8 (0.6)
Copper (µg/L)	29.6 (8.8)	29.2 (12.2)	28.2 (8.7)	27.9 (11)
Iron (µg/L)	556.7 (122.2)	637.8 (256.2)	690 (170.1)	552.7 (189.1)
Lead (µg/L)	21.2 (12.4)	27 (17.4)	21.5 (11.6)	32.6 (24.3)
Mercury (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)
Nickel (µg/L)	14.8 (4.5)	16.1 (6.7)	16.5 (5.8)	14.8 (5.1)
Silver (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)
Zinc (µg/L)	427.8 (180.9)	402.2 (173.9)	426.7 (186.8)	359.3 (184.3)
Total PAHs (ng/L)	58.4 (9.8)	67.3 (33.3)	55.2 (9.9)	54.5 (35.7)
Dissolved Metals				
Aluminum (µg/L)	94.5 (54.7)	76.6 (47)	60.3 (9.1)	25.5 (36.1)
Cadmium (µg/L)	0.6 (1)	0.6 (1)	0.8 (0.9)	0.4 (0.9)
Chromium (µg/L)	2 (0.5)	1.8 (0.9)	2.1 (0.7)	1.7 (0.6)
Copper (µg/L)	22.2 (8.4)	18.7 (11.5)	22.3 (8.9)	18.7 (9.7)
Iron (µg/L)	166.6 (112.6)	147.8 (138.9)	183.2 (127.2)	142 (111.8)
Lead (µg/L)	11.3 (10)	13.6 (13.8)	11.8 (10)	19.3 (21.4)
Mercury (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)
Nickel (µg/L)	12.2 (4.8)	10.9 (6.8)	13.3 (5.1)	11 (5.5)
Silver (µg/L)	0 (0)	0 (0)	0 (0)	0 (0)
Zinc (µg/L)	320 (166.9)	334.4 (187.4)	318.3 (171.9)	286.3 (185.3)

accumulation of solids and other pollutants on road and parking lot surfaces (Pitt and Shawley 1981, Asplund *et al.* 1982, Kerri *et al.* 1985). Wind is also a well-known mechanism for resuspending particles for atmospheric transport and deposition (Williams 1982, Slinn and Slinn 1980). Chemical processes can also limit the accumulation of potential pollutants on parking lot surfaces. For example, Hewitt and Rashad (1992) reported that between 70 and 99% of PAHs were removed from the road environment either by the atmosphere, volatilization, photo-oxidation, or other oxidation processes. We did not find substantial accumulation of PAHs in our study.

Pressure washing was more effective than street sweeping for removing accumulated pollutants during this study. While the comparison between these two management practices was somewhat biased because we measured directly before and after pressure washing and not for street sweeping, it is readily apparent that weekly sweeping activities produced virtually no benefit. This may be due to two factors: (1) maximum accumulation rates are less than one week, in which case we may have missed any street sweeping benefit; or (2) street sweeping only collects large debris and leaves behind smaller particles that contain the majority of the pollutants. We presume it is the latter factor since other studies (Pitt 1985, Maestri *et al.* (1985), and Gupta *et al.* (1981) reported that intensive street cleaning conducted three times a week using traditional mechanical street cleaners showed no significant improvement in runoff water quality and was only effective in removing large solids. Most recently, Sutherland and Jelen

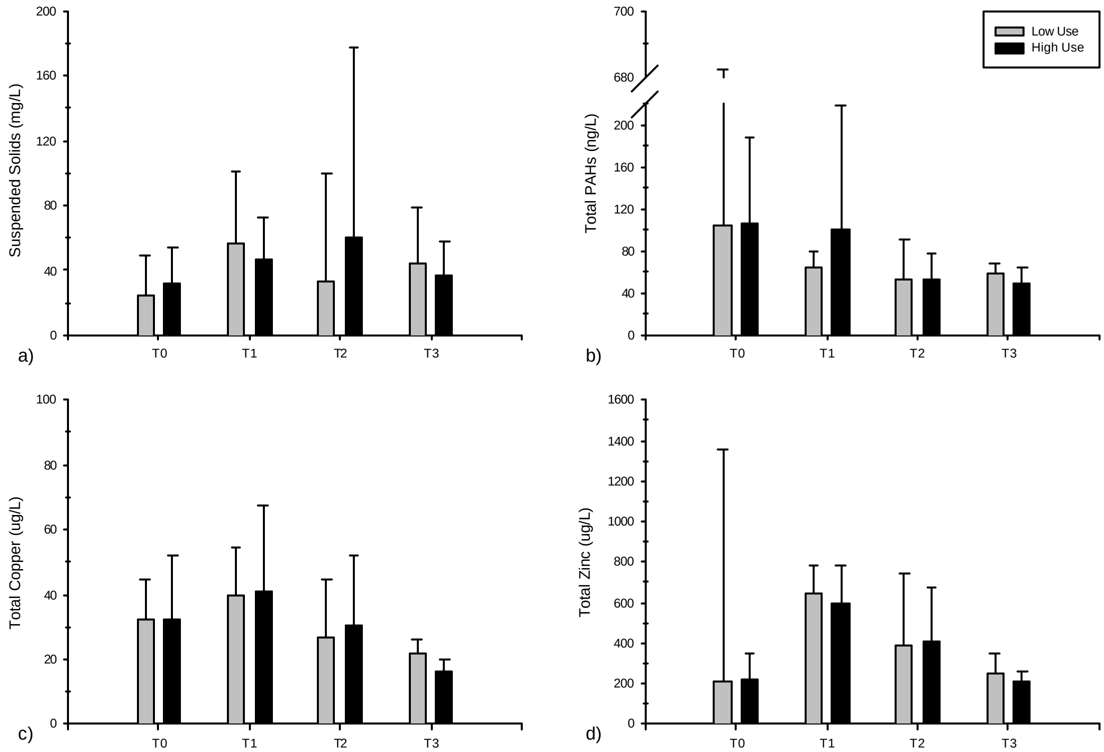

FIGURE 2. Mean concentrations (± 95% C.I.) of (a) suspended solids, (b) total PAHs, (c) total copper and (d) total zinc in runoff from low-use and high-use parking lots over time.

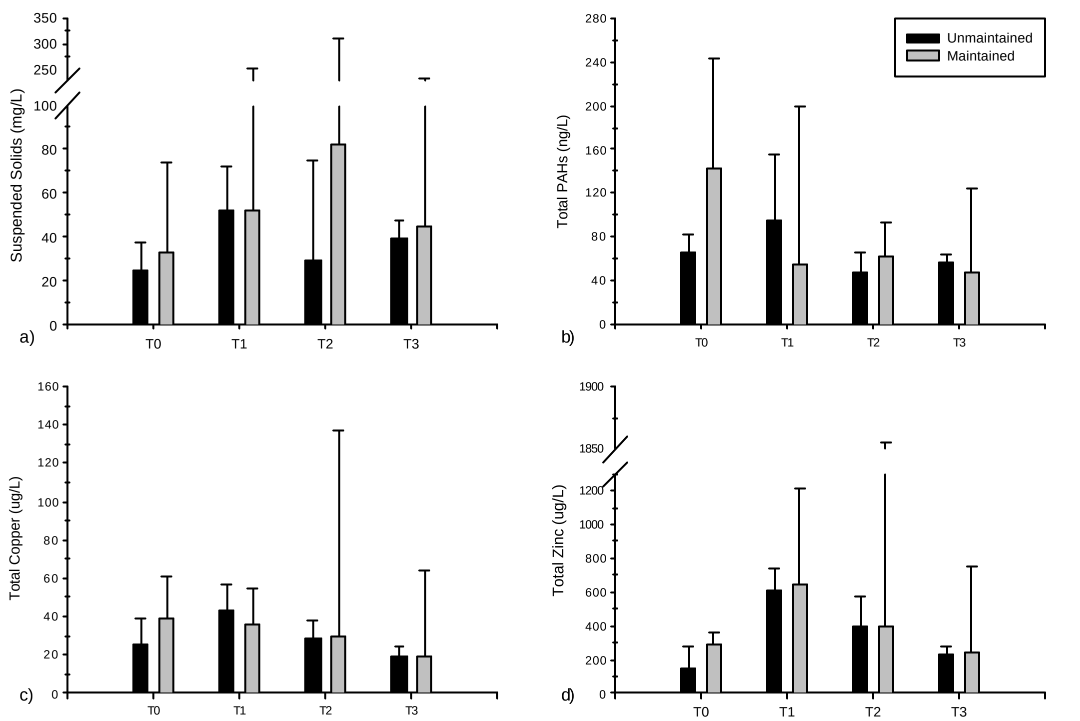

FIGURE 3. Mean concentrations (± 95% C.I.) of (a) suspended solids, (b) total PAHs, (c) total copper and (d) total zinc in runoff from maintained and unmaintained parking lots over time.

(1997) and Claytor (1999) have evaluated the use of vacuum-assisted sweepers and regenerative-air sweepers to determine an optimum sweeping frequency. These improved sweeping mechanisms removed finer street surface materials than the standard mechanical street cleaning equipment, with measurable improvements in pollutant removal efficiency obtained with a sweeping frequency once every week.

Vehicles are one of the major sources of pollutants in parking lot runoff (Hahn and Pfeifer 1994, Asaeda *et al.* 1996). Therefore, the amount of traffic on a given parking lot should influence the accumulation of pollutants on the parking lot surface. However, our study did not establish a strong relationship between traffic volume and increased contaminant concentrations. Similarly, runoff concentrations from highways of different traffic densities found a weak correlation between TSS and average daily traffic (ADT), and no correlation of metal loadings with ADT (McKenzie and Irwin [1983], Boucier *et al.* [1980]. In another study, Stotz [1986]) concluded that the amount of pollutants discharged had a higher correlation to the physical characteristics of the area than the traffic frequency. Once again, these data support a physically dominated accumulation rate.

Parking lots remain a source of concern for managers charged with improving runoff water quality. The pollutant concentrations we observed in this study were similar to measurements of roadways by others (i.e., Ellis *et al.* 1987, Gupta *et al.* 1981, Hoffman *et al.* 1985, Sansalone and Buchberger 1997), but higher than concentrations measured in other land uses. For example, zinc concentrations in this study were three-fold to four-fold higher than average zinc concentrations from residential land uses sampled throughout southern California (Ackerman and Schiff 2003). Moreover, the concentrations of several dissolved trace metals, including zinc, in parking lot runoff measured after one month of accumulation was well above the State of California water quality objective for protection to aquatic life. In addition, dissolved zinc has been identified as the likely constituent in urban stormwater runoff responsible for toxicity to marine organisms (Schiff *et al.* 2003; Jirik *et al.* 2001). To this end, managers will need to continue investigating best management practices for controlling parking lot runoff in southern California at frequencies of less than one month.

LITERATURE CITED

Ackerman, D. and K. Schiff. 2003. Estimates of stormwater mass emissions to the Southern California Bight. *Journal of Environmental Engineering* 129: 308-317.

Asaeda, T., V.T. Ca and A. Wake. 1996. Heat storage of pavement and its effect on the lower atmosphere. *Atmospheric Environment: Urban Atmosphere* 30: 413-427.

Asplund, R.L., J.F. Ferguson and B.W. Mar. 1982. Total suspended solids in highway runoff in Washington state. *Journal of the Environmental Engineering* 108: 391-404.

Bannerman, R.T., D.W. Owens, R.B. Dodds and N.J. Hornewer. 1993. Sources of pollutants in Wisconsin stormwater. *Water Science Technology* 28: 241-259.

Boucier, D.R., I. Hinden and J.C. Cook. 1980. Titanium and tungsten in highway runoff at Pullman, Washington. *International Journal of Environmental Studies* 15: 145-149.

Claytor, R. 1999. New developments in street sweeper technology. Center for Watershed Protection, Ellicott City, MD. *Watershed Protection Techniques* 3:601-604.

Ellis, J.B., D.M. Revitt, D.O. Harrop and P.R. Beckwith. 1987. The contribution of highway surfaces to urban stormwater sediments and metal loadings. *The Science of the Total Environment* 59: 339-349.

Gupta, M.K., R.W. Agnew, D. Gruber and W. Kreutzberger. 1981. Constituents of highway runoff volume. IV: Characteristics of runoff from operating highways. FHWA/RD-81/045. Envirex, Inc. Milwaukee, WI.

Hahn, H.H. and R. Pfeifer. 1994. The contribution of parked vehicle emissions to the pollution of urban run-off. *The Science of the Total Environment* 146/147: 525-533.

Herricks, E. 1995. A context for understanding stormwater effects in receiving systems. pp. 3-8 *in:* E. Herricks (ed.), Stormwater Runoff and Receiving Systems: Impact, monitoring, and assessment. CRC Press. Boca Raton, FL.

Hewitt, C.H. and M.B. Rashad. 1992. Removal rates of selected pollutants in the runoff-waters from a major rural highway. *Water Research* 26: 311-319.

Hoffman, E.J., J.S. Latimer, C.D. Hunt, G.I. Mills and J.G. Quinn. 1985. Stormwater runoff from highways. *Water, Air, and Soil Pollution* 25: 349-364.

Jirik, Andrew, S.M. Bay, D.J. Greenstein, A. Zellers and S.L. Lau. 1998. Application of TIEs in studies of urban stormwater impacts on marine organisms. pp. 284-289 *in:* E.E. Little, A.J. DeLonay and B.M. Greenberg (eds.), Environmental Toxicology and Risk Assessment: Seventh Volume. ASTM STP 1333. American Society for Testing and Materials. Philadelphia, PA.

Kerri, K.D., R.B. Howell and J.A. Racin. 1985. Forecasting pollutant loads from highway runoff. *Transportation Research Record* 1017: 39-46.

Leecaster, M. K., K. Schiff and L. Tiefenthaler. 2002. Assessment of efficient sampling designs for urban stormwater monitoring. *Water Research* 36: 1556-1564.

Maestri, B., C.W. Burch and F. Hohnson. 1985. Management practices for mitigation of highway stormwater runoff pollution, Vol. IV. FHWA/RD-85/004. Federal Highway Administration. McLean, VA.

McKenzie, D.J. and G.A. Irwin. 1983. Water quality assessment of stormwater runoff from a heavily used urban highway bridge in Miami, Florida. FHWA/FL/BMR-84-270. U.S. Geologic Survey. Miami, FL.

Muschack, W. 1990. Pollution of street run-off by traffic and local conditions. *The Science of the Total Environment* 93: 419-431.

Pitt, R. 1985. Characterizing and controlling urban runoff through street and sewerage cleaning. EPA/600/S2-85/038, PB 85-186500. United States Environmental Protection Agency, Storm and Combined Sewer Program, Risk Reduction Engineering Laboratory. Cincinnati, OH.

Pitt, R. and G. Shawley. 1981. San Francisco Bay Area National Urban Runoff Project. A demonstration of non-point source pollution management on Castro Valley Creek, Main Report. Alameda County Flood Control and Water Conservation District. Alameda County, CA.

Pitt, R. and R. Sutherland. 1982. Washoe County Urban Stormwater Management Program, Vol. 2, Street particulate data collection and analyses. Washoe Council of Governments. Reno, NV.

Sansalone, J.J. and Buchberger, S.G., 1997. Partitioning and first flush of metals in urban roadway storm water. *Journal of Environmental Engineering* 123: 134-143

Schiff, K., S. Bay, and D. Diehl. Stormwater toxicity in Chollas Creek and San Diego Bay. *Environmental Monitoring and Assessment* 81: 119-132.

Schueler, T. 1997. The importance of imperviousness. *Watershed Protection Techniques* 3:100-111.

Shaheen, D.G. 1975. Contributions of urban roadway usage to water pollution. EPA 600/2-75-004. Environmental Protection Agency. Washington, DC.

Shaver, E., J. Maxted, G. Curtis and D. Carter. 1995. Watershed protection using an integrated approach, in stormwater NPDES related monitoring needs. Engineering Foundation, American Society of Civil Engineers. Crested Butte, CO.

Slinn, S. and W. Slinn. 1980. Predictions of particle deposition on natural waters. *Atmospheric Environment* 14: 1013-1016.

Smith, D.L. and B.M. Lord. 1990. Highway water quality control - summary of 15 years of research. *Transportation Research Record* 1279: 69-74.

Stotz, G. 1986. Investigations of the properties of the surface water runoff from federal highways. FRG Proceedings of 2nd International Symposium - Highway Pollution 59:329-338.

Sutherland, R.C. and S.L. Jelen. 1997. Contrary to conventional wisdom, street sweeping can be an effective BMP. Computational Hydraulics International. Guelph, Ontario.

Tiefenthaler, L.L. and K. Schiff. In press. Accumulation characteristics of contaminant concentrations on a parking lot. *Journal of the American Water Resources Association*.

United States Environmental Protection Agency (U.S. EPA). 1991. Methods for the determination of metals in environmental samples. EPA/600/4-91/010. Office of Research and Development, United States Environmental Protection Agency. Washington, DC.

Williams, R. 1982. A model for the dry deposition of particles to dry deposition to natural waters. *Atmospheric Environment* 16: 1933-1938.

ACKNOWLEDGEMENTS

The authors wish to thank Property Prep Inc. and Wastewater Remediation for construction of the rainfall simulators. The authors are also indebted to the following SCCWRP personnel, who assisted in this project: Jeffrey Brown, Ehren Doris, Kim Johnson, and Julie Kalman assisted with toxicity studies and field sampling; Andrea Steinberger and Dario Diehl assisted with field preparation and sampling; and David Tsukada assisted with field sampling and TSS analysis.