Assessment of best management practice (BMP) effectiveness for reducing toxicity in urban runoff

Jeffrey Brown and Steven Bay

Abstract

To assess the effectiveness of Best Management Practices (BMPs) in southern California for improving water quality impacts related to toxicity, five BMP technologies were evaluated with respect to their ability to reduce contaminant concentrations and toxicity in runoff samples. The BMP technologies included an enhanced stream wetland, constructed sub-surface flow wetland cells, a screening/settlement sump, hydrodynamic devices using Continuous Deflection Separation (CDS) units, and a combination of screening, microfiltration, and UV treatment. BMPs based on wetland systems were able to reduce many of the total and dissolved metals, as well as diazinon, in the runoff samples . Dissolved metals that were not reduced were either too low to expect large reductions, or were below chronic water quality criteria in the inflow. Toxicity for wetlands was rare, and was reduced after treatment. Most of the CDS unit devices were ineffective or inconsistent at reducing metal concentrations or toxicity, and had mixed results with total suspended solids (TSS). In general, the CDS units also had no effect on toxicity. This is not surprising, as the CDS units were designed to remove solids from runoff, yet the fraction usually associated with toxicity is the dissolved phase. The screening/settlement sump was inconsistent in reducing most metals and TSS. Although sample toxicity was often reduced after screening/settlement sump treatment, outflow samples remained highly toxic. The SMURRF site used a combination of treatment processes that consistently reduced concentrations of most total metals and TSS, however few metals were high enough to assess attainment of the chronic criteria. Toxicity for this site was not consistent enough to evaluate reduction.

Introduction

Best Management Practices (BMPs) are used extensively in southern California to reduce contaminants in urban runoff (Caltrans 2004, Strecker *et al.* 2004). The BMPs are extremely varied and may include public education, installation of treatment facilities/devices, the routing of runoff through grassy/wetland habitats, or diversion of runoff to sanitary sewers. Most BMPs that treat urban runoff are designed to reduce or remove trash, nutrients, or toxic constituents associated with particulates. Previous studies have examined the effectiveness of BMPs with regards to contaminant removal in southern California (Caltrans 2004, Strecker *et al.* 2004). For example, the Caltrans 2004 study determined that BMPs that use infiltration or sand filtration technologies were among the most effective for reducing levels of total suspended solids (TSS), total nutrients, and total metals.

In contrast, information regarding changes in toxicity is comparatively limited. Aquatic toxicity has been measured in runoff samples in Ballona Creek, Los Angeles River, Santa Ana River, San Diego Creek, and Chollas Creek (Schiff *et al.* 2003, Bay *et al.* 1997). Because of the many chemical constituents found in runoff, measurements obtained using a routine suite of chemicals alone does not give a complete assessment of changes made by the BMP. However, toxicity measurement can improve the evaluation of BMP effectiveness as this helps to account for unmeasured contaminants. In addition, such measurements incorporate the additive and antagonistic interactions of chemicals as a direct measure of effect. Moreover, many structural BMPs are not capable of reducing the most toxic fraction of runoff, the dissolved phase. Therefore, even when BMPs have been shown to reduce the larger particulates found in runoff, it cannot be assumed that treatment processes are also reducing toxicity. Consequently, direct measurement of toxicity is needed.

The goal of this project was to assess the effectiveness of BMPs in southern California for reducing water quality impacts related to toxicity. Collaborative monitoring programs were established with local research and stormwater management agencies that implement BMPs in the southern California coastal area. Samples of stormwater or dry-weather flow from upstream and downstream of the BMPs were analyzed for toxicity to aquatic life and contaminant concentration associated with runoff toxicity.

Methods

Approach

Seven BMP sites representing five BMP technologies were assessed for their effectiveness to reduce contaminant concentrations and toxicity (Figure 1). The five BMP technologies included wetlands, hydrodynamic devices (e.g., continuous deflection separation (CDS) units), microfiltration, UV treatment, and screening/settlement. Samples were collected both before and after the BMP treatment processes in order to evaluate the effectiveness of each BMP system. Each BMP was assessed for its ability to reduce toxicity and concentrations of pollutants to levels below water quality criteria.

Four to five sampling events were conducted for each site (Table 1). Paired inflow/outflow samples of dry-weather or stormwater runoff were collected between February 2, 2004 and March 10 2005. Two sites were sampled only during storm events, and three sites were sampled only during dry-weather flow. One other site was sampled during both storm and dry-weather events. Finally, two constructed experimental wetland cells were dosed with a mixture of Cu, Zn, and diazinon over a six week period. The wetland cells were dosed because the inflow water for these cells did not contain contaminant concentrations that were sufficient to evaluate removal effectiveness. Time-weighted composite samples were collected at most BMP sites, with multiple grabs collected and composited at two of the sites.

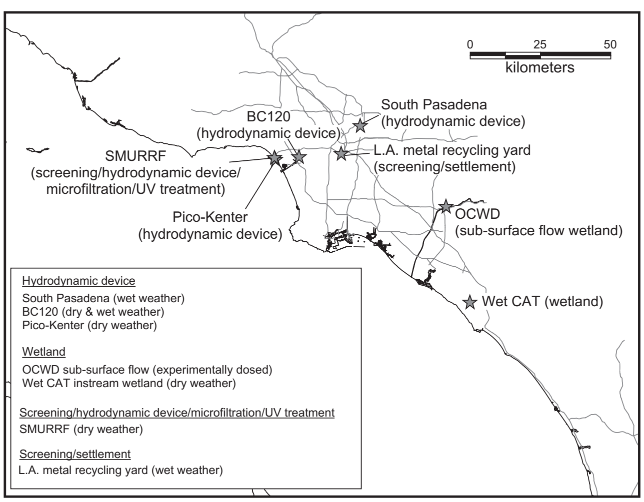

Figure 1. BMP sampling locations. The type of sample collected for this study (dry- or wet-weather) is indicated in the figure legend. Los Angeles and Orange County freeways have been added for reference.

Samples from each site were analyzed for toxicity (echinoderm fertilization test, and *Ceriodaphnia dubia* (*C. dubai*) survival and reproduction test) and metals (Table 2). Most BMP inflow and outflows were also analyzed for organophosphorus pesticides, and a subset were also measured for pyrethroid pesticides, and glyphosate (active ingredient in Roundup™ and Rodeo™). Differences among the constituents analyzed reflect that while most of the data in this study were collected specifically for this investigation, some of the data were obtained through parternship with other monitoring programs that measured fewer parameters. Analytical methods and reporting levels among the analytical laboratories were generally consistent (Table 2).

Technologies evaluated

Wetlands

<u>Wet CAT (wetland)</u>

The Wetland Capture and Treatment network (Wet CAT) was designed to treat low-flow urban runoff from a residential neighborhood in the Aliso Creek watershed. The major processes that reduce contaminants in wetland systems include settling, microbial degradation, and uptake by wetland plants. The Wet Cat site was designed to treat flows of approximately 0.2 cfs, with measured flows at 0.15 cfs in the summer and 0.12 cfs in the fall of 2003. The hydraulic residence time was three days. While there are three distinct wetlands in the Wet CAT network, this study focused on the largest one, known as the West wetland. The West wetland is a 1.4 acre, 0.5-mile long parcel of land on the west side of Alicia Parkway in Laguna Niguel. The West wetland treats 317 acres of exclusively urban runoff. Only dry-weather runoff samples from the Wet CAT site were collected for this study. Samples were collected at the head of the wetland and as the water left the wetland.

<u>OCWD (sub-surface flow constructed wetland)</u>

The other wetland BMP in this study was the Orange County Water Department (OCWD) sub-surface flow (SSF) constructed wetlands, located next

Table 1. Sampling event descriptions for each BMP in this study.

Site	Sampling event	Sample date	Type of sample	Antecedent dry weather period (days)	Flow volume sampled (gallons)
Wet CAT wetland (dry)	1 Inflow	11/17/04	Composite (time weighted)	8	203,773
	1 Outflow	11/18/04	Composite (time weighted)	9	208,167
	2 Inflow	12/15/04	Composite (time weighted)	6	163,815
	2 Outflow	12/16/04	Composite (time weighted)	7	169,486
	3 Inflow	1/19/05	Composite (time weighted)	7	51,534
	3 Outflow	1/20/05	Composite (time weighted)	8	50,673
	4 Inflow	3/9/05	Composite (time weighted)	5	65,559
	4 Outflow	3/10/05	Composite (time weighted)	6	64,347
OCWD sub-surface wetland (experimental dosing)	1	2/3/05	Composite (multiple grabs)	5	Approx. 1,440
	2	2/10/05	Composite (multiple grabs)	12	Approx. 1,440
	3	2/24/05	Composite (multiple grabs)	0	Approx. 1,440
	4	3/3/05	Composite (multiple grabs)	7	Approx. 1,440
	5	3/10/05	Composite (multiple grabs)	6	Approx. 1,440
Pico-Kenter hydrodynamic device (dry)	1	11/18/04	Composite (time weighted)	9	Not measured
	2	12/16/04	Composite (time weighted)	7	Not measured
	3	1/20/05	Composite (time weighted)	8	Not measured
	4	3/10/05	Composite (time weighted)	6	Not measured
BC120 hydrodynamic device (dry)	1	1/19/05	Composite (time weighted)	7	11,176
	2	3/10/05	Composite (time weighted)	6	3,217
BC120 hydrodynamic device (wet)	1	1/26/05	Composite (flow weighted)	14	284,257
	2	2/11/05	Composite (flow weighted)	13	4,911,939
South Pasadena hydrodynamic device (wet)	1	12/5/04	Composite (time weighted)	5	55,475
	2	1/2/05	Composite (time weighted)	1	30,954 (toxicity); 163,113 (chemistry)
	3	1/7/05	Composite (time weighted)	1	20,332 (toxicity); 1,307,639 (chemistry)
	4	1/26/05	Composite (time weighted)	14	12,066 (toxicity); 13,884 (chemistry)
	5	2/11/05	Composite (time weighted)	12	39,677 (toxicity); 304,322 (chemistry)
SMURRF UV/filtration/ hydrodynamic device (dry)	1	11/18/04	Composite (time weighted)	9	201,907
	2	12/16/04	Composite (time weighted)	7	25,900
	3	1/20/05	Composite (time weighted)	8	333,043
	4	3/10/05	Composite (time weighted)	6	234,788
L.A. metal recycling yard screening/settlement (wet)	1	2/2/04	Composite (multiple grabs)	14	4,309
	2	2/18/04	Composite (multiple grabs)	15	27,460
	3	10/26/04	Grab	5	Not measured
	4	2/11/05	Grab	13	Not measured

Table 2. Constituent methods and reporting levels used to analyze runoff samples.

	SMURRF, Pico-Kenter, Wet CAT, BC120		L.A. metal recycling yard		South Pasadena	
Analyte	**Reporting Level**	**Method**	**Reporting Level**	**Method**	**Reporting Level**	**Method**
Total and dissolved metals (µg/L)						
As	0.5	EPA 200.8	0.5	EPA 200.8	1.0	EPA 200.8
Cd	0.2	EPA 200.8	0.2	EPA 200.8	0.25	EPA 200.8
Cr	0.5	EPA 200.8	1.0	EPA 200.8	0.5	EPA 200.8
Cu	0.5	EPA 200.8	1.0	EPA 200.8	0.5	EPA 200.8
Fe	5.0	EPA 200.8	100	EPA 200.7	100	EPA 236.1
Pb	0.5	EPA 200.8	0.5	EPA 200.8	0.5	EPA 200.8
Hg	0.1	EPA 200.8	0.1	EPA 7470A	0.2	EPA 245.1
Ni	0.5	EPA 200.8	1.0	EPA 200.8	1.0	EPA 200.8
Se	0.5	EPA 200.8	1.0	EPA 200.8	1.0	EPA 200.8
Zn	0.5	EPA 200.8	5	EPA 200.8	1.0	EPA 200.8
Organics (µg/L)						
Organophosphate Pesticides	0.01-0.02	EPA 625	Not analyzed		0.01-2.00	EPA 507
Pyrethroids	0.01-0.025	EPA 625	Not analyzed		Not analyzed	
Glyphosate	6	EPA 547	Not analyzed		Not analyzed	

to OCWD's Field Research Laboratory, near Anaheim Lake. These wetlands consist of 1 m tall x 2 m wide x 8 m long cells that are constructed from concrete panels. Each wetland cell is filled with fl" pea gravel. A monoculture of wetland plants (bulrushes, genus Scirpus) are planted in the gravel. The gravel provides an approximate thousand-fold increase in surface area for the growth of bacterial biofilms that increase the rate of contaminant degradation or removal. Within the gravel matrix there are distinct oxygen rich (aerobic) and oxygen free (anaerobic) zones where specific microbial processes take place. Water flows beneath the surface of the gravel matrix. The source water for the wetlands comes from Conrock Basin, which receives wet- and dry-weather flow from the Santa Ana River. The advantages of SSF wetlands are less land area required for a system, the elimination of vector problems, and viable operation in winter. The wetland cells were constructed in 2002.

The OCWD SSF was the only BMP in this study that was experimentally dosed with contaminants. Two replicate wetland cells were used in this study. Each cell was continuously dosed with a mixture of Cu, Zn, and diazinon and monitored over a six week period. The nominal concentrations flowing into each cell were 30 µg/L Cu, 60 µg/L Zn, and 0.4 µg/L diazinon. Concentrations of each contaminant were measured in the influent and effluent from each replicate system over five sampling periods. The samples were also analyzed for toxicity using the sea urchin fertilization test. The flow rate for the source water from Conrock Basin was maintained at 4 L/minute. Two stock solutions (one for Cu and Zn, and one for diazinon) were created and diluted to working solutions on a daily basis. The working solutions were added to each wetland cell on a continuous basis using peristaltic pumps.

The flow rates for the working solutions were maintained at 5 mL/minute. Filters made from montmorillonite clay and granular activated carbon were used to recover any remaining amounts of contaminants from the effluent that were not removed by the wetlands.

Hydrodynamic devices (CDS units)

Three of the BMP sites (Pico-Kenter, BC120, and South Pasadena) used CDS Technologies' Continuous Deflective Separation (CDS) hydrodynamic devices. These devices use a vortex and screening process to remove solids from wet- and dry-weather runoff. The components of a CDS unit consist of a sump, separation chamber (which contains a stationary screen cylinder), and diversion weir. Particles within the diverted treatment flow are retained by a deflective screen and maintained in a circular motion, forcing the particles to the center of the separation chamber, which creates an enhanced swirl concentration of solids (vortex separation) until they settle into the sump.

Pico-Kenter (hydrodynamic device)

The Pico-Kenter CDS unit is located at the end of Pico Boulevard near the beach in Santa Monica and operated by the City of Santa Monica. It receives a mix of runoff from approximately 4,200 acres of western Los Angeles County, which includes commercial, residential, and transportation land uses. The effluent from this CDS unit feeds into the Santa Monica Urban Runoff Recycling Facility (SMURRF; see below).

BC120 (hydrodynamic device)

The BC120 CDS unit is located near Ballona Creek, in Culver City. It receives runoff from approximately 4,077 acres of Culver City and drains into Ballona Creek at Overland Avenue.

South Pasadena (hydrodynamic device)

The South Pasadena CDS unit is located near the intersection of Orange Grove and El Centro, in the City of South Pasadena and operated by the Los Angeles County Department of Public Works (LACDPW). It receives runoff from 6 acres comprised of approximately 70% residential, 20% industrial, and 10% other.

Screening/hydrodynamic device/microfiltration/ UV treatment

SMURRF (Screening/hydrodynamic device/microfiltration/UV treatment)

The Santa Monica Urban Runoff Recycling Facility (SMURRF) treats dry-weather flow using a combination of technologies, including 2-mm^2 screening, a hydrodynamic device to remove sand and grit, microfiltration to remove turbidity (effluent turbidity <2 ntu), and ultraviolet radiation to kill pathogens (Boyle Engineering Corp. 1999). This system is designed to treat up to 500,000 gallons of runoff per day. Water from this facility is used for City landscaping and government toilets. This BMP site is located adjacent to the Santa Monica Pier and receives runoff from approximately 5,100 acres of commercial, residential, and transportation activities. Most of the runoff treated by SMURRF is first passed through the Pico-Kenter CDS unit. A smaller amount of runoff is received from the Santa Monica pier storm drain.

Screening/settlement

L.A. metal recycling yard (screening/settlement)

The BMP at the L.A. metal recycling yard is an infiltration trench that uses screening and settlement to prevent larger particles from entering the trench. Water from the site flows into a 3 m x 3 m x 0.7 m sump, where settlement of the heavier particles occurs. The water then flows through a screen mesh into the infiltration trench. Samples were collected before the water entered the sump and after it had passed through the screen mesh. Approximately 0.85 acres of the recycling yard is treated by the BMP. This BMP treats runoff that is exclusive to this site and monitored only during wet-weather events.

Sampling methods

Wet CAT, Pico-Kenter, BC120, SMURRF

The samples from the Wet CAT, Pico-Kenter, BC120, and SMURRF sites were collected using similar methods among sites. Samples from each of these sites were collected with American Sigma 900 Max Autosamplers configured with 19-L borosilicate jars. Flow monitors (American Sigma 950 Area Velocity Bubbler Flowmeters) were used at each site, with the exception of Pico-Kenter, where flow meters could not be installed due to the non-ideal configuration. The components of each monitoring system used were calibrated for time and sample-aliquot volume prior to deployment. The autosamplers at these sites collected 200 mL aliquot inflow and outflow samples every 15 minutes for 24 hours. Because the flow at the SMURRF site was intermittent (treatment occurred only when sufficient volume of runoff had accumulated), the autosamplers were triggered by flowmeters only in response to effluent flow. Most of these sites used paired autosamplers to collect the inflow and outflow samples simultaneously. At the Wet CAT site, however, sampling of the outflow was delayed by 24 hours after the start of inflow collection, in an attempt to account for the hydraulic residence time of the wetland.

OCWD SSF

Five sampling events were captured at the OCWD SSF site. At approximately weekly intervals, 2-L composite samples of inflow and outflow samples were collected from each wetland for chemical and toxicity analysis. Three manual grab samples were collected over 24 hours and composited. The flow rate was monitored and adjusted by visual inspection using a sight glass flow meter.

South Pasadena

Five stormwater sampling events were captured at the South Pasadena site. The samples for toxicity testing were collected every 20 minutes and composited usually for 3 hours during the initial part of each storm. The samples for chemical analysis were also collected every 20 minutes and composited, but the sample duration was usually longer, lasting from 3 hours up to 4 days.

L.A. metal recycling yard

Four stormwater sampling events were captured at the L.A. metal recycling yard. Multiple grab samples were collected and composited for the first two events, while single grab samples were collected for the other two events.

Toxicity testing

Dry-weather and wet-weather samples were tested for toxicity using the 7-day *C. dubia* survival and reproduction test (USEPA 1994). All tests were started within 2 days of sample collection. The samples were tested at three concentrations (100%, 50%, and 25% runoff). Ten replicates were included in each test. The test endpoints were percent survival and the number of offspring. A concurrent copper reference toxicant test was conducted with each testing event. Each test included a laboratory control consisting of moderately hard freshwater. A salt blank, consisting of freshwater adjusted to the salinity of the test sample, was included in some of the tests. Test solutions were changed on a daily basis, and the organisms were fed each day. Dissolved oxygen, conductivity, pH, and temperature were measured each day. Alkalinity, hardness, and total ammonia were measured at the beginning of each experiment. Water quality measurements during the test met the test recommended ranges.

The echinoderm fertilization test was also used (USEPA 1995). This test measured toxic effects on sea urchin or sand dollar sperm as a reduction in ability to fertilize eggs. Purple sea urchins (*Strongylocentrotus purpuratus*) were used in the majority of tests, while sand dollars (*Dendraster excentricus*) were used for the November 2004 tests due to the lack of spawning sea urchins. The tests consisted of a 20 minute exposure of sperm to samples of 12.5%, 25%, or 50% runoff that were adjusted to a salinity of 32 g/kg using hypersaline brine. Eggs were then added and 20 minutes allowed for fertilization to occur. The eggs were then preserved and examined later with a microscope to assess the percentage of successful fertilization. Toxic effects were expressed as a reduction in fertilization percentage. The tests were conducted in glass shell vials containing 10 mL of solution at a temperature of 15°C. Four replicates were tested for each sample. Laboratory seawater was included as a control. A concurrent reference toxicity test with Cu was conducted with each testing event.

Chemical analysis

All samples were analyzed for total and dissolved metals. The samples from the SMURRF, Pico-Kenter, WetCAT, and BC120 sites were also analyzed for organophosphate (OP) pesticides, pyrethroid pesticides, and glyphosate. The samples from the South Pasadena and OCWD SSF sites were analyzed for OP pesticides in addition to metals. Variation in the constituents among sites reflects the multiple monitoring programs contributing data. While the samples in this study were analyzed by multiple organizations, the testing procedure and reporting levels were generally consistent (Table 2).

Data analysis

Toxicity

Data from the echinoderm and *C. dubia* tests were evaluated for significant reductions in fertilization, survival, or reproduction using analysis of variance (ANOVA) with Dunnett's test, or Steel's Many-One rank test when assumptions of normality or homoscedasticity were not met. Comparisons were made against the seawater control for the echinoderm fertilization test and against the laboratory dilution water control for the *C. dubia* test. Using this approach, the highest concentration of runoff that did not cause significant toxicity (the no effect concentration; NOEC) was estimated for each inflow and outflow sample.

Median-effect concentrations (LC50 or EC50) were also calculated. These are the concentrations of runoff that caused a 50% reduction in survival (LC50), or reproduction or fertilization (EC50). Toxicity units were then calculated to compare the magnitude of response. Toxic units (TU) were derived as 100/LC50 or 100/EC50. A TU >1 was considered to be a strong toxic response. Because the highest concentration of runoff sample tested with the echinoderm fertilization test was 50%, the lowest TU that could be calculated was 2. Therefore, absence of toxicity in the 50% sample would be associated with TU <2. The lowest concentration of runoff in the fertilization test was 12.5%. Therefore in cases with extreme toxicity where the EC50 <12.5%, the associated TU would be >8.

Chemistry

A tiered approach was used to evaluate BMP effectiveness. In the first tier of the BMP effectiveness evaluation, the magnitude of the difference in concentrations between inflow and outflow samples was examined. The percent reduction between inflow and outflow contaminant concentrations was calculated for each BMP site as:

$$\frac{Influent - Effluent}{Influent}\, x(100)$$

For those samples with a $\geq$10% reduction between inflow and outflow concentrations, the second tier of the BMP effectiveness evaluation, which compared the outflow concentrations to chronic water quality criteria, was used. While water quality criteria are not currently used to assess regulatory compliance of the runoff in this study, these criteria are useful for determining protective levels of concentrations in the inflow and outflow. California Toxics Rule values were used for total Se, as well as for dissolved As, Cd, Cu, Ni, Pb, and Zn; there are no chronic criteria for dissolved Ag, Al, Cr(3+6), Se or Sn. For total Al, chlorpyrifos, and malathion, the national freshwater chronic water quality criteria were used; for diazinon, the California Department of Fish and Game freshwater chronic criterion was used. In cases for which at least two inflow samples exceeded the water quality criterion, the relationship of the outflow concentration to the water quality criterion was examined.

The concept that a 10% reduction between inflow and outflow concentrations is meaningful was derived from measures of analytical variability. Analytical variability was estimated from the relative percent difference (RPD) among sample duplicates that were measured as part of the quality assurance program in this study.

Table 3. Toxicity in inflow and outflow samples from each BMP site. NA = not analyzed. NOEC = No Effect Concentration (the highest concentration of sample tested that did not cause an effect, relative to the control). TU = toxic units.

	Event 1		Event 2		Event 3		Event 4		Event 5	
	NOEC (%)	TU	NOEC (%)	TU	NOEC (%)	TU	NOEC (%)	TU	NOEC (%)	TU
Wet CAT wetland										
Echinoderm fertilization inflow	50	<2	50	<2	<12.5	3.1	<12.5	>8		
Echinoderm fertilization outflow	50	<2	50	<2	50	<2	25	2.2		
C. dubia survival inflow	50	2.4	100	<1	100	<1	100	<1		
C. dubia survival outflow	100	<1	100	<1	100	<1	100	<1		
C. dubia reproduction inflow	NA	NA	NA	NA	NA	NA	100	<1		
C. dubia reproduction outflow	NA	NA	NA	NA	NA	NA	100	<1		
OCWD Wetland cell #1										
Echinoderm fertilization inflow	25	<2	50	<2	50	<2	50	<2	25	<2
Echinoderm fertilization outflow	50	<2	50	<2	50	<2	50	<2	50	<2
OCWD Wetland cell #2										
Echinoderm fertilization inflow	50	<2	50	<2	50	<2	50	<2	50	<2
Echinoderm fertilization outflow	50	<2	50	<2	50	<2	50	<2	50	<2
Pico-Kenter CDS										
Echinoderm fertilization inflow	50	<2	25	1.7	25	<2	<12.5	<2		
Echinoderm fertilization outflow	50	<2	25	2.1	25	2.3	12.5	1.1		
C. dubia survival inflow	100	<1	100	<1	NA	NA	100	<1		
C. dubia survival outflow	100	<1	100	<1	NA	NA	100	<1		
C. dubia reproduction inflow	NA	NA	NA	NA	NA	NA	100	<1		
C. dubia reproduction outflow	NA	NA	NA	NA	NA	NA	100	<1		
BC120 CDS dry-weather										
Echinoderm fertilization inflow	25	2.4	50	<2						
Echinoderm fertilization outflow	12.5	3.0	<12.5	<2						
C. dubia survival inflow	NA	NA	100	<1						
C. dubia survival outflow	NA	NA	100	<1						
C. dubia reproduction inflow	NA	NA	100	<1						
C. dubia reproduction outflow	NA	NA	100	<1						
BC120 CDS wet-weather										
Echinoderm fertilization inflow	<12.5	>8	25	2.6						
Echinoderm fertilization outflow	<12.5	>8	25	2.9						
C. dubia survival inflow	NA	NA	100	<1						
C. dubia survival outflow	NA	NA	100	<1						
C. dubia reproduction inflow	NA	NA	100	<1						
C. dubia reproduction outflow	NA	NA	100	<1						

Table 3. continued

	Event 1		Event 2		Event 3		Event 4		Event 5	
	NOEC (%)	TU	NOEC (%)	TU	NOEC (%)	TU	NOEC (%)	TU	NOEC (%)	TU
South Pasadena CDS										
Echinoderm fertilization inflow	12.5	3.3	<12.5	5.0	<12.5	>8	<12.5	>8	12.5	30.5
Echinoderm fertilization outflow	12.5	3.6	<12.5	7.1	<12.5	>8	<12.5	>8	<12.5	27.5
C. dubia survival inflow	100	<1	100	<1	100	<1	>100	<1	>100	<1
C. dubia survival outflow	100	<1	100	<1	100	<1	>100	<1	>100	<1
C. dubia reproduction inflow	100	<1	100	<1	100	<1	>100	<1	>100	<1
C. dubia reproduction outflow	100	<1	100	<1	100	<1	>100	<1	>100	<1
SMURRF										
Echinoderm fertilization inflow	50	<2	25	2.5	<12.5	1.2	25	<2		
Echinoderm fertilization outflow	6.25	8.7	<12.5	>8	<12.5	>8	25	<2		
C. dubia survival inflow	100	<1	100	<1	100	<1	100	<1		
C. dubia survival outflow	50	1.4	100	<1	100	<1	100	<1		
C. dubia reproduction inflow	NA	NA	NA	NA	NA	NA	100	<1		
C. dubia reproduction outflow	NA	NA	NA	NA	NA	NA	100	<1		
L.A. metal recycling yard BMP										
Echinoderm fertilization inflow	<12.5	>8	<12.5	>8	12.5	2.5	<12.5	>8		
Echinoderm fertilization outflow	<12.5	>8	12.5	5.4	50	<2	<12.5	>8		
C. dubia survival inflow	<25	>4	100	<1	6.25	16.0	25	2.2		
C. dubia survival outflow	<25	>4	25	2.1	12.5	8.3	50	1.4		
C. dubia reproduction inflow	<25	>4	6.25	9.4	<6.25	7.0	<25	6.7		
C. dubia reproduction outflow	<25	>4	12.5	5.2	12.5	5.7	<25	5.9		

In this study, 120 pairs of laboratory duplicate analyses for metals were analyzed. Most of the pairs had RPD values of <10%, indicating that analytical variability was usually less than 10% for both dissolved and total metals. Therefore, differences of ≥10% for the inflow and outflow metals data were greater than expected for analytical variability, and are probably meaningful. The 10% difference rule was also applied to TSS and pesticides, although these constituents did not have enough duplicate measurements to determine the level of analytical variability.

Results

Changes in toxicity

The two wetland BMPs were effective in reducing toxicity (Table 3). Both the Wet CAT wetland and the OCWD SSF wetland reduced the toxicity in two of the sampling events. The TU of the November inflow sample at the Wet CAT site decreased from 2.4 to <1 with respect to the survival test and from >8 to 2.2 in the March event with respect to the fertilization test. None of the samples at the OCWD SSF site reduced sea urchin fertilization by 50%; therefore, the TU was <2 for all samples. However, significant toxicity in two of the inflow samples was observed. The threshold effect value (NOEC) for the two sampling events improved following treatment from a threshold of 25% for the inflow samples to 50% for the outflow samples (fertilization test).

The *C. dubia* survival and reproduction results for samples from the Wet CAT site were influenced by dissolved salts. While survival and reproduction were consistently low in these samples (0 - 55% survival, 0 offspring), toxicity was usually equivalent to the salt blank that was tested concurrently with the Wet CAT samples. In a previous study, concentrations of dissolved salts associated with conductivity values greater than 1.8 - 2.8 ms caused impairment to *C. dubia* reproduction (Brown and Bay 2003). In the present study, the conductivity values in all Wet CAT samples exceeded this threshold range by a factor of at least two. Toxicity due to other contaminants could only be resolved in the November inflow sample. While the conductivity value was relatively high in this sample, the survival was significantly lower than that found in the salt control. The high salt content did not cause interference with the echinoderm fertilization test, because hypersaline brine was added to the samples to bring the conductivity level up to approximately 54 ms.

In general, the CDS units had no effect on the toxicity (Table 3). Most of the inflow and outflow samples from each of the CDS units were toxic to sea urchin fertilization, with no improvement following treatment. In addition, there was no difference between the wet- and dry-weather samples at BC120 (the only site with both wet- and dry-weather samples) in terms of the effectiveness of toxicity removal.

The toxicity data for the samples from the SMURRF site could not be used to evaluate toxicity removal effectiveness. Although the inflow samples from two of the events were toxic to echinoderm fertilization, reductions in toxicity could not be assessed because of the influence of added chlorine. As part of the treatment process at SMURRF, chlorinated water is used to backflush the screens. Previous studies have shown that the echinoderm test is sensitive to chlorine, with an approximate median effect threshold of 0.02 mg/L (Dinnel *et al.* 1981). In the present study, residual chlorine concentrations in the outflow samples from SMURRF were 12 to 33 times this value in the samples from November, December, and January. The increased toxicity was probably not due to other contaminants, as the other dissolved contaminants analyzed at SMURRF either remained fairly constant or declined between inflow and outflow samples. There was no consistent toxicity to *C. dubia*.

Outflow samples from the screening/settlement device at the L.A. metal recycling yard were usually quite toxic, although toxicity was often slightly lower following treatment (Table 3). This slight decrease was not consistent enough to indicate that the BMP apparatus was able to affect toxicity. For example, *C. dubia* survival improved following treatment for two sampling events (from 16 TU to 8 TU in the October 2004 event, and from 2.2 TU to 1.4 TU in the February 2005 event), however the BMP apparatus appeared to induce toxicity for the February 2004 event (from <1 TU to 2.1 TU following treatment). For the fourth sampling event at this site, toxicity to sea urchin fertilization was high and unaffected by the treatment.

Effectiveness of metals removal

Both wetland BMP systems (Wet CAT and OCWD SSF) showed great potential to reduce concentrations of total and dissolved metals. A consistent reduction in the concentrations of total Cd, Cu, Ni and Zn, and dissolved Al, Cd, Ni and Zn between inflow and outflow samples from the Wet CAT site

Table 4. Range of percent removal of contaminants for each BMP type evaluated in this study. NA = not analyzed. ND = not detected.

	Wetland		Hydrodynamic device (CDS)				Screening / hydrodynamic device / microfiltration / UV treatment	Screening / settlement
Analyte	Wet CAT	OCWD SSF	Pico-Kenter	BC120 (dry)	BC120 (wet)	South Pasadena	SMURRF	LA Metal Recycling Yard
General				Range of % removal				
Dissolved Organic Carbon	0 – 6.7	NA	0 – 10	0, 10	-91, (-4)	NA	6 – 12	-238 – 24
Ammonia	>17 - >88	NA	-60 - 40	-50, 10	-67, 0	-31 – 57	-100 – 64	-108 – 15
Conductivity	-6 – 5	NA	-0.1 – 5	-3, 0.3	-60, (-6)	NA	-1 – 2	-61 – 15
TDS	-5 – 1	NA	-17 – 16	-7, 72	5, ND	-422 – 67	- 6 – 13	-71 – 16
TSS	31 – 90	NA	-300 – 19	50, 73	-97, (-6)	-57 – 97	94 – 99	-179 – 69
Metals								
As (total)	-12 – 12	NA	-64 – 95	-4, 0.5	-26, (-21)	ND	-7 – 12	-214 – 48
Cd (total)	97 – 99	NA	ND	ND	-41, (-3)	ND	ND, 33	-110 – 29
Cr (total)	4 – 25	NA	-91 – (-2)	9, 14	-50, (-32)	-40 – 55	18 – 41	-5.1 – 52
Cu (total)	20 – 29	64 – 94	-84 – 3	13, 26	-46, (-34)	-6 – 26	47 – 59	-16 – 58
Pb (total)	-54 – ND	NA	-1161 – 40	32, 33	-53, (-7)	-49 – 80	79 – 97	-66 – 48
Hg (total)	ND	NA	ND	-14	ND	ND	ND	-135 – 52
Ni (total)	75 – 84	NA	-344 – 2	9, 16	-36, (-30)	-34 – 30	24 – 66	-3.3 – 45
Se (total)	10 – 18	NA	-11 – 8	-6, (-5)	-4, ND	ND	-108 – 2	<(-595) – 3
Zn (total)	64 – 91	75 – 98	-375 – 6	24, 33	-31, (-14)	-26 – 28	52 – 68	-156 – 33
As (dissolved)	-32 – 5	NA	-5 – 5	-1, 0	-35, (-2)	ND	11 – 65	-45 – >59
Cd (dissolved)	65 – 99	NA	ND - 0	ND, 29	25, ND	ND	ND	-602 – 54
Cr (dissolved)	-44 – 20	NA	-8 – 13	2, 6	-247, 1	-104 – 5	-16 – 7	36 – 79
Cu (dissolved)	-27 – 10	53 – 93	-3 – 11	-0.6, 0.4	-82, (-5)	-60 – 19	-38 – 6	2 – 50
Pb (dissolved)	ND	NA	0 – 13	-3, 15	-40, (-0.4)	-51 – 58	ND – 29	-54 – 87
Hg (dissolved)	ND	NA	ND	ND	ND	ND	ND	-35 – 18
Ni (dissolved)	76 – 85	NA	-2 – 8	-6, 0.8	-97, (-3)	-20 – 6	-1 – 11	-47 – 47
Se (dissolved)	0.5 – 14	NA	-16 – 21	-7, 0.8	18, ND	ND	-12 – 2	-452 – 5
Zn (dissolved)	43 – 82	75 – 100	-6 – 17	-10, 29	-42, 18	-33 – (-4)	10 – 34	-2009 – (-57)
Diazinon	ND – >67	-14 – >92	ND	ND, 0	ND, 50	ND, 21	ND	NA

was observed (Tables 4 and 5). For those metals with water quality criteria, the Wet CAT wetland system was very effective at reducing concentrations of dissolved Cd and Ni, and total Al to levels below established thresholds (Table 6). For other dissolved metals, including dissolved Zn, concentrations below the chronic criterion were observed in the inflow samples; therefore, the ability of the Wet CAT system to attain the water quality criterion could not be evaluated (Tables 6 and 7). This system was not able to reduce concentrations of dissolved Cu by more than 10%, however dissolved Cu levels were quite low in the inflow samples (≤11 µg/L) from this site. For the SSF wetlands, concentrations of total and dissolved Cu and Zn were consistently reduced by at least 50% in the outflow samples. This site was also effective at consistently reducing concentrations of dissolved Cu to levels below the chronic criterion. Dissolved Zn levels, while greatly reduced in the outflow samples, never exceeded the chronic criterion in the inflow samples (Table 7).

The BMPs using hydrodynamic devices were generally ineffective at reducing metal concentrations by ≥10%, for metals with chronic water quality criteria. The CDS unit at the BC120 site was able to reduce concentrations of total metals in the dry-weather samples, but water quality criteria for these constituents do not exist. Concentrations of total Al were reduced by >10% in both dry-weather outflow samples from the BC120 site, although the outflow concentrations were never reduced below the chronic criterion. Concentrations of most total metals, including total Al, As, Cd, Cr, Cu, Pb, Ni and Zn, increased in at least one of the wet-weather samples from the BC120 site after treatment (Table 4). Most increases were more than 10%. For example, concentrations of total Cu increased by 46% (from 90 to 131 μg/L) for the first wet-weather event and by 34% (from 26 to 36 μg/L) for the second wet-weather event. Increases in total metals were also observed for at least one sampling event from the Pico-Kenter CDS unit, with concentrations of total As, Cd, Cu, Cr, Ni, Pb, and Zn increasing by more than 50%.

The BMP for the SMURRF site was effective in reducing concentrations of most total metals by 10%, but less effective in reducing concentrations of most dissolved metals (Table 5). The treatment process consistently reduced concentrations of total Al, Cr, Cu, Ni, Pb, and Zn, and dissolved Al and Zn by ≥10%, but was not able to effectively reduce levels of total As and Se or dissolved As, Cr, Cu, and Se. Dissolved metals in the SMURRF site inflow were consistently below chronic water quality criteria; therefore, attainment of the water quality criteria could not be evaluated. However, total Al values were reduced to levels below the chronic criterion.

The screening/settlement apparatus at the L.A. metal recycling yard was usually effective at reducing concentrations of dissolved Cu and Pb by ≥10%. Dissolved Pb was reduced to levels below the chronic criterion half of the time, while dissolved Cu was never reduced below the criterion. This BMP was not effective for reducing any of the other metals with chronic criteria. Dissolved Cr was the only metal constituent without a chronic criterion to be consistently reduced by ≥10%. A consistent increase in concentrations of total and dissolved Cd and dissolved Zn following treatment was observed. Concentrations of total and dissolved Cd increased for three out of the four sampling events, with total Cd levels in the outflow up by as much as 110% (from 9 to 19 μg/L) and dissolved Cd up by as much as 601% (from 0.7 to 5.2 μg/L). Dissolved Zn increased in the outflow for all four sampling events, by as much as 2009% (from 33 to 696 μg/L).

Effectiveness of pesticide removal

Diazinon and malathion were the only pesticides detected in any of the Wet CAT wetland samples. Diazinon was reduced by a factor of >3 in one sample event, and by a factor of 2 in the other event for which this pesticide was detected. Inflow concentrations for the Wet CAT site were insufficient to evaluate attainment of the water quality criterion. Malathion was reduced by a factor of >7 for the only sampling event with detectable amounts of this pesticide. Malathion levels were below the water quality criterion for both the inflow and outflow samples.

The OCWD SSF system was able to reduce diazinon concentrations by >10% for 8 out of 9 sampling events (from 12% to >92%). For one sampling event however, concentrations were similar between the inflow and outflow samples. Only the outflow sample for the first sampling event was below the chronic water quality criterion. The reason for reduction in the effectiveness of diazinon removal after the first event is unclear; however, the most likely explanation is that lack of diazinon in the outflow during the first week was due to inconsistencies in the dosing of the wetlands. The dosing of the metals solution at the OCWD SSF site used a different delivery system and was not affected.

Chlorpyrifos was detected in two of the sampling events for the South Pasadena CDS site. Concentrations of chlorpyrifos were similar between inflow and outflow samples for one of the events, but an apparent 67% increase in chlorpyrifos was observed for the other sampling event. Hence this BMP was not effective in removing this OP pesticide. Pesticides were not detected at any other BMP site with enough frequency to determine reduction effectiveness.

Effectiveness of TSS removal

Numerical water quality criteria do not exist for TSS; consequently, the BMPs in this study were only evaluated for their ability to reduce concentrations of TSS by at least 10%. The Wet CAT wetland was able to reduce TSS for all sampling events captured, presumably because the long residence time allowed sedimentation processes to occur. A previous study found an average TSS reduction of 23% for the Wet CAT site (CH2MHill 2004), which is less than the 74% average reduction observed for this study.

Mixed results for the CDS units were observed. TSS was reduced by >10% in both of the dry-weather samples from BC120 (from 51 to 14 mg/L for the first event and 17 to 8 mg/L for the second event); however, TSS was not reduced in the wet-weather samples from this site (from 204 to 217 mg/L for the

Table 5. Proportion of sampling events with >10% reduction between inflow and outflow samples. NA = not analyzed. ND = not detected.

	Wet CAT (wetland) Dry-weather	OCWD (sub-surface flow wetland) Experimental dosing	Pico-Kenter (CDS) Dry-weather	BC120 (CDS) Dry-weather	BC120 (CDS) Wet-weather	South Pasadena (CDS) Wet-weather	SMURRF (filtration + UV) Dry-weather	L.A. metal recycling yard (grit removal) Wet-weather
Total metals								
Al	3/4	NA	1/4	2/2	0/2	2/4	4/4	2/4
As	1/4	NA	1/4	0/2	0/2	ND	1/4	2/4
Cd	4/4	NA	ND	ND	0/2	ND	1/1	1/4
Cr	3/4	NA	0/4	1/2	0/2	2/5	4/4	1/4
Cu	4/4	5/5 (cell#1 & #2)	0/4	2/2	0/2	2/5	4/4	1/4
Ni	4/4	NA	0/4	1/2	0/2	2/5	4/4	2/4
Pb	0/2	NA	2/4	2/2	0/2	3/5	4/4	2/4
Se	4/4	NA	0/4	0/2	0/1	ND	0/4	0/4
Zn	4/4	5/5 (cell#1 & #2)	0/4	2/2	0/2	3/5	4/4	2/4
Dissolved metals								
Al	4/4	NA	2/4	0/2	0/2	ND	4/4	1/2
As	0/4	NA	0/4	0/2	0/2	ND	0/4	2/3
Cd	4/4	NA	0/1	1/1	1/1	ND	ND	1/4
Cr	2/4	NA	2/4	0/2	0/2	0/4	0/4	4/4
Cu	1/4	5/5 (cell#1 & #2)	1/4	0/2	0/2	1/5	0/4	3/4
Ni	4/4	NA	0/4	0/2	0/2	0/3	1/4	2/4
Pb	0/1	NA	0/2	1/2	0/2	0/3	1/2	3/4
Se	1/4	NA	2/4	0/2	1/1	ND	0/4	0/4
Zn	4/4	5/5 (cell#1 & #2)	1/4	1/2	1/2	0/5	4/4	0/4
Total suspended solids	4/4	NA	2/4	2/2	0/2	3/5	4/4	2/4
Organophosphorus pesticides								
Chlorpyrifos	ND	NA	0/1	ND	ND	1/2	ND	NA
Diazinon	2/2	3/4 (cell#1) 5/5 (cell#2)	ND	0/1	1/1	1/1	ND	NA
Malathion	1/1	NA	ND	ND	ND	ND	1/1	NA
Pyrethroid pesticide	ND	NA	ND	ND	ND	NA	ND	NA
Bifenthrin	ND	NA	ND	0/1	ND	ND	ND	NA
Glyphosate	ND	NA	ND	ND	ND	NA	ND	NA

Table 6. BMP effectiveness with regard to chronic water quality criteria. Denominators indicate the number of inflow samples that exceeded water quality criteria, while numerators indicate the number of outflow samples that met the criteria only after treatment. Instances for which the inflow sample was below the water quality criteria prior to treatment were not counted. NA = not analyzed. * = outflow sample from 1/2/05 met the water quality criterion only because the hardness of the outflow sample increased substantially relative to the inflow sample, thereby increasing the criterion; these samples are not identified as meeting the chronic criteria after treatment in this table.

	Wet CAT (wetland) Dry-weather	OCWD (sub-surface flow wetland) Experimental dosing	Pico-Kenter (CDS) Dry-weather	BC120 (CDS) Dry-weather	BC120 (CDS) Wet-weather	South Pasadena (CDS) Wet-weather	SMURRF (filtration + UV) Dry-weather	L.A. metal recycling yard (grit removal) Wet weather
Total metals								
Al	3/4	NA	0/3	0/2	0/2	0/3	4/4	0/2
Se	0/4	NA	0/1	0/0	0/0	0/0	0/1	0/3
Dissolved metals								
As	0/0	NA	0/0	0/0	0/0	0/0	0/0	0/0
Cd	3/3	NA	0/0	0/0	0/0	0/0	0/0	0/0
Cu	0/0	5/5 (cell#1) 2/2 (cell#2)	1/1	0/2	0/2	0/5	0/0	0/4
Ni	2/2	NA	0/0	0/0	0/0	0/0	0/0	0/1
Pb	0/0	NA	0/0	0/1	0/1	1*/3	0/0	2/4
Zn	0/0	0/0 (cell#1) 0/0 (cell#2)	0/0	0/1	0/2	0*/4	0/0	0/1
OP pesticides								
Chlorpyrifos	0/0	NA	0/0	0/0	0/0	0/2	0/0	NA
Diazinon	0/0	0/4 (cell#1) 1/5 (cell#2)	0/0	0/0	1/1	1/1	0/0	NA

Table 7. Overall effectiveness of BMP treatment. The evaluation of the BMP efficiency used a two-tier approach: tier 1 assessed the ability of the BMP to reduce concentrations by >10%; tier 2 assessed the ability to attain a water quality criterion. The results of the tiered approach were designated as follows. For tier 1, reductions less than 10% were given a "No" designation, while reductions of >10% (for at least 75% of the sampling events) were designated "Yes". Instances of insufficient data to determine consistent reduction (e.g., measurements usually below the reporting level) are indicated by "U" (uncertain). For tier 2, "+" indicates that the BMP reduced the outflow sample concentration to below the chronic criterion, and a "-" indicates the BMP was unable to meet the criterion. A "U" designation was used for tier 2 if concentrations were below the criterion in the inflow, or when there was insufficient data to assess a reduction. A "?" was used when the criterion was met inconsistently. NA = not analyzed.

	Wet CAT (wetland) Dry-weather	OCWD (sub-surface flow wetland) Experimental dosing	Pico-Kenter (CDS) Dry-weather	BC120 (CDS) Dry-weather	BC120 (CDS) Wet-weather	South Pasadena (CDS) Wet-weather	SMURRF (filtration + UV) Dry-weather	L.A. metal recycling yard (grit removal) Wet-weather
Total metals								
Al	Yes/+	NA	No/–	Yes/–	No/–	No/–	Yes/+	No/–
Se	Yes/–	NA	No/U	No/U	U/U	U/U	No/U	No/–
Dissolved metals								
As	No/U	NA	No/U	No/U	No/U	U/U	No/U	No/U
Cd	Yes/+	NA	U/U	U/U	U/U	U/U	U/U	No/U
Cu	No/U	Yes/+	No/U	No/–	No/–	No/–	No/U	Yes/–
Ni	Yes/+	NA	No/U	No/U	No/U	U/U	No/U	No/U
Pb	U/U	NA	U/U	No/U	No/U	No/U	U/U	Yes/?
Zn	Yes/U	Yes/U	No/U	No/U	No/–	No/–	Yes/U	No/–
OP pesticides								
Chlorpyrifos	U/U	NA	U/U	U/U	U/U	No/–	U/U	NA
Diazinon	Yes/U	Yes/–	U/U	U/U	U/U	U/U	U/U	NA

first sampling event and from 80 to 140 mg/L during the second event). TSS reduction was inconsistent in the samples from the Pico-Kenter and South Pasadena sites. Overall, the removal ability of the CDS units in this study did not appear to be related to inflow TSS concentrations, although most inflow TSS levels were <250 mg/L. The greatest TSS reduction (97% removal) was associated with an inflow concentration (868 mg/L) that was much higher than the other initial TSS levels in this study.

The microfiltration process used at the SMURRF site consistently reduced the TSS levels by more than 10%. Removal efficiencies ranged from 94% - 99% TSS removal, with starting concentrations ranging from 8 - 44 mg/L. The screening/settlement process used at the L.A. metal recycling yard was not able to consistently reduce TSS levels. TSS levels were reduced by 25% and 69% from starting concentrations of 320 and 440 mg/L, respectively, for two of the sampling events. However, for one other sampling event, TSS levels were unchanged (1,200 mg/L in both inflow and outflow) after treatment, and for another sampling event, TSS levels increased (from 61 mg/L TSS in the inflow to 170 mg/L in the outflow). Remobilization of particles that had settled out is a possible explanation for this increase.

Reduction in TSS is not a parameter of direct relevance to water column toxicity, as contaminants usually need to be in the dissolved form to produce effects on organisms under laboratory exposure conditions. However, TSS removal does correspond to reductions in particle-associated contaminants, which could have a beneficial impact on sediment toxicity or bioaccumulation from feeding. The study design and analytical methods used in this study were not sufficient to assess potential impacts on sediment toxicity. Different procedures for sample collection and testing are needed to assess the toxicity associated with runoff particles.

Discussion

The wetland BMPs had the best overall combination of toxicity and contaminant reduction. The toxicity was consistently reduced (although not completely removed in all samples from the Wet CAT site) by both wetland systems. In addition, both wetland BMPs were better able to reduce contaminants by at least 10% and better able to meet chronic water quality criteria than the other BMP types in this study (Table 7). Reductions in toxicity and contaminants for the wetland sites is facilitated by major processes such as settling, microbial degradation, and uptake by wetland plants. These processes are enhanced by, and require, the longer residence time in wetlands. The half-mile long stretch of wetland and added berms at the Wet CAT site provide for a three-day hydraulic residence time, while the flow rate through the OCWD sub-surface flow wetland cells is controlled manually.

In general, the hydrodynamic devices (e.g., CDS units) had no effect on toxicity. This is not surprising, as CDS units were designed to remove solids from runoff and exhibited little effect on the dissolved metals in this study; dissolved metals are the forms most likely to cause water column toxicity. Improvements in toxicity for about half of the samples following treatment by the grit removal system at the L.A. metal recycling yard were observed. However despite the improvement, the outflow samples usually remained quite toxic.

Previous investigators have shown that BMPs can have lower percent removal rates when inflow concentrations are low (Caltrans 2004). This issue appears to be particularly relevant for dissolved Cu at the Wet CAT site, as this system was able to reduce the levels of other dissolved metals with greater inflow concentrations. The issue of low inflow concentrations is also a reason to use caution when considering the range of removal efficiencies results in Table 4, because the data in this table do not take into account the inflow concentrations for any of the constituents listed. The lower efficiency for dissolved metals reduction at SMURRF and the Pico-Kenter sites may also be a function of the low inflow concentrations; however, it is more likely that this lower efficiency is due to these BMPs' lack of treatment processes to reduce dissolved metals.

Increases in contaminant concentrations following treatment by some of the BMPs were observed. Concentrations of total and dissolved Cd and dissolved Zn were consistently higher following treatment by the screening/settlement device at the L.A. metal recycling yard, while total metals tended to increase in the wet-weather samples from the CDS unit at the BC120 site and in one of the samples from the Pico-Kenter CDS unit. It is unclear what causes the increase in metal concentrations, but possible explanations include resuspension and remobilization of contaminants that have been collected by the devices (for the particle-bound metals) and oxidation/reduction processes of dissolved phase metals during periods of dry weather.

In order to determine whether or not the increase in metal concentrations by the CDS units was typical of other studies, the chemistry data were compared with the International Stormwater BMP Database. This database contains inflow and outflow data for metals and TSS that has been collected over the past decade from several types of BMPs (Strecker *et al.* 2004); however, this database does not currently include toxicity data. Dissolved Cu and Zn data from the present study were compared to the inflow/outflow 95% prediction interval for hydrodynamic devices from the international database. Most of the data from the CDS units used in this study fell within the prediction interval (Figure 2). However, one of the CDS unit samples (BC120 wet-weather sample) exceeded the upper prediction limit for total Cu, while two samples (one BC120 wet-weather sample, and one Pico-Kenter sample) exceeded the upper prediction limit for total Zn. Therefore, some of the increases in concentration following treatment at these sites was not typical of the performance at other sites with hydrodynamic devices.

The data from all of the BMPs in this study were compared with biofiltration BMPs in the international database. Biofiltration BMPs (which include grass strips and swales) are believed to be one of the most effective types of BMPs currently in use (E. Strecker, personal communication). Comparison to biofiltration BMPs was used to evaluate how the BMPs in this study relate to one of the best available BMP treatment processes.

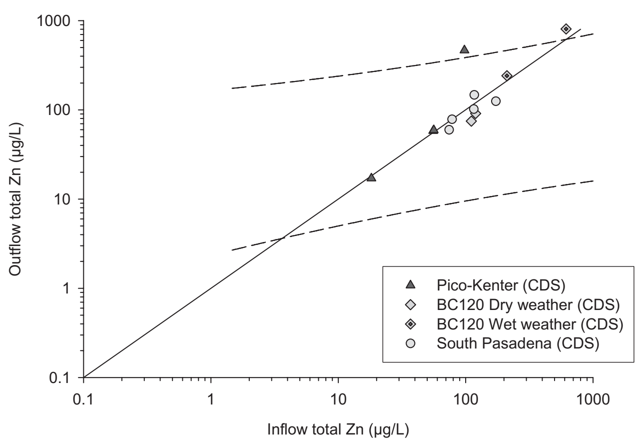

Figure 2. Total zinc concentrations in the inflow and outflow samples from the CDS unit sites. The solid line demonstrates a one-to-one relationship between total zinc concentrations in inflow and outflow samples. The dashed lines represent the upper and lower 95% prediction intervals for hydrodynamic devices in the International Database.

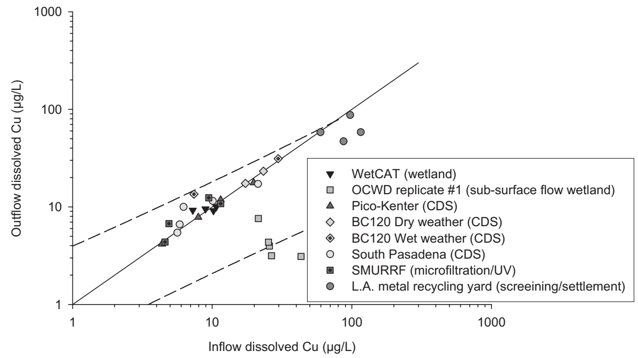

Figure 3. Dissolved copper concentrations in the inflow and outflow samples from each of the BMP study sites. The solid line demonstrates a one-to-one relationship between dissolved copper concentrations in these inflow and outflow samples. The dashed lines represent the upper and lower 95% prediction intervals for the International Database.

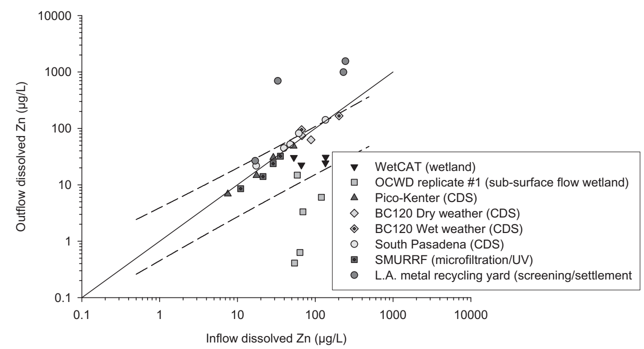

Figure 4. Dissolved zinc concentrations in the inflow and outflow samples from each of the BMP study sites. The solid line demonstrates a one-to-one relationship between dissolved zinc concentrations in the inflow and outflow samples. The dashed lines represent the upper and lower 95% prediction intervals for the International Database.

For dissolved Cu and Zn, most of the data from the present study fell within the prediction limits from the international stormwater database (Figures 3 and 4). However, the OCWD SSF wetland was often at, or below the lower prediction level for both dissolved Cu and Zn, indicating that this BMP performed better than most of the biofiltration BMPs in the international database. Conversely, the grit removal system at the L.A. metal recycling yard usually exceeded the upper prediction level for dissolved Zn, indicating a poorer removal efficiency than the biofiltration BMPs. For TSS, only the data from SMURRF and the Wet CAT sites were below the biofilter lower prediction limit, while the

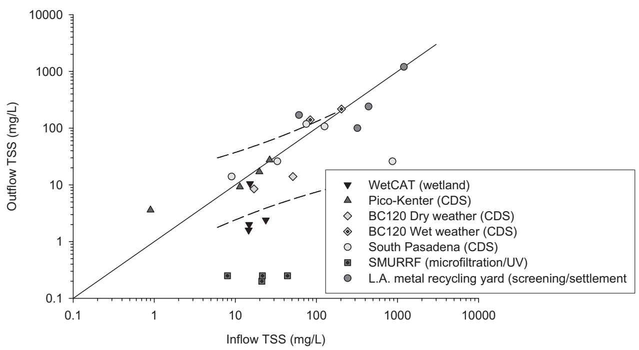

Figure 5. Total suspended solids concentrations in the inflow and outflow samples from each of the BMP study sites. The solid line demonstrates a one-to-one relationship. The dashed lines represent the upper and lower 95% prediction intervals for the International Database.

wet-weather flow from the BC120 site consistently exceeded the upper prediction limit (Figure 5).

This study expands understanding of BMP effectiveness under field conditions in southern California, adding new information for sites that have not been examined previously, and assesses additional constituents of concern for aquatic life protection (e.g., toxicity, OP pesticides) at sites that have been studied before. The assessment of treatment effectiveness described in this study is intended to provide information regarding the technologies examined and not designed to evaluate the suitability of specific BMPs at the study sites. The BMPs included in this study were installed for purposes other than removal of aquatic life toxicity, and the results show that, with the exception of systems that included biological treatment, toxicity removal effectiveness cannot be assumed.

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