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Remediation and Restoration

BIOSWALES REDUCE CONTAMINANTS ASSOCIATED WITH TOXICITY IN URBAN STORM WATER

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Abstract: Contamination and toxicity associated with urban storm water runoff are a growing concern because of the potential impacts on receiving systems. California water regulators are mandating implementation of green infrastructure as part of new urban development projects to treat storm water and increase infiltration. Parking lot bioswales are low impact development practices that promote filtering of runoff through plants and soil. Studies have demonstrated that bioswales reduce concentrations of suspended sediments, metals, and hydrocarbons. There have been no published studies evaluating how well these structures treat current-use pesticides, and studies have largely ignored whether bioswales reduce toxicity in surface water. Three storms were monitored at 3 commercial and residential sites, and reductions of contaminants and associated toxicity were quantified. Toxicity testing showed that the majority of untreated storm water samples were toxic to amphipods (*Hyalella azteca*) and midges (*Chironomus dilutus*), and toxicity was reduced by the bioswales. No samples were toxic to daphnids (*Ceriodaphnia dubia*) or fish (*Pimephales promelas*). Contaminants were significantly reduced by the bioswales, including suspended solids (81% reduction), metals (81% reduction), hydrocarbons (82% reduction), and pyrethroid pesticides (74% reduction). The single exception was the phenypyrazole pesticide fipronil, which showed inconsistent treatment. The results demonstrate these systems effectively treat contaminated storm water associated with surface water toxicity but suggest that modifications of their construction may be required to treat some contaminant classes. *Environ Toxicol Chem* 2016;35:3124–3134. © 2016 SETAC

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INTRODUCTION

Urban runoff may contain high levels of pesticides, nutrients, metals, suspended solids, and hydrocarbons. Monitoring of dry season and storm water runoff has indicated that there are widespread pollution and toxicity problems associated with agriculture and urban runoff in freshwater and coastal habitats throughout California [1]. These include acute toxicity to aquatic organisms and associated ecological impacts to invertebrate communities [2–6]. Recent monitoring has shown that much of the toxicity is linked to current-use pesticides associated with urban runoff [6–8]. To protect the beneficial uses of aquatic habitats, the State of California is now encouraging incorporation of low impact development (LID) design principles in new urban developments under National Pollution Discharge Elimination System permits [9]. Low impact development is a storm water management strategy aimed at maintaining or restoring the natural hydrologic functions of watersheds by employing development features that reduce the rate of runoff, filter pollutants, and facilitate groundwater infiltration [10].

The Central California Regional Water Quality Control Board now requires incorporation of LID designs in all new urban construction projects. Several larger developments in Salinas (CA, USA) in the central coast region of California have implemented LID practices such as construction of bioswales, which act as the primary treatment and water capture system for parking lot runoff during storm events. Bioswales are vegetated drainage courses with sloped sides that trap sediments and treat contaminants. Research and site-specific evaluations have established that bioswales are effective at slowing and capturing water, settling sediments, and reducing nutrients, metals, and hydrocarbons in the runoff [10]. There has been little research to date on the effectiveness of bioswales in reducing toxicity to aquatic organisms, but several related studies have recently assessed toxicity reductions to fish using a bench scale experimental soil bioretention column [11–13]. Few published studies have evaluated how well green infrastructure treatment systems treat current-use pesticides in storm water.

Determining the capacity of urban bioswales and other treatment systems to reduce contamination and surface water toxicity is an important consideration when selecting strategies to minimize impacts of regional urban storm water runoff. The current project was designed to evaluate the effectiveness of bioswales at reducing the concentrations of contaminants that routinely contribute to storm water toxicity in California. Three parking lot bioswale sites in Salinas were sampled during 3 storm events over 2 yr to evaluate storm water treatment efficacy. The results provide data to storm water regulatory agencies, water quality managers, LID design engineers, and others involved in storm water management, and are intended to be used in future planning and management decisions related to storm water recovery and aquatic life protection.

METHODS

Study sites

The 3 study sites were selected to represent commercial and residential land uses, and all had asphalt parking areas showing no signs of recent repaving or resealing. Two sites were in the Boronda Crossing Shopping Center in northwestern Salinas. This shopping center hosts several larger department stores and smaller retail outlets. The Boronda sites consisted of 2 bioswales that treated runoff from parking spaces in front of

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a Kohl's® retail store (hereafter, Kohl's), and a smaller site in front of a Chili's® restaurant (hereafter, Chili's). A third site was a residential housing complex approximately 9 km east of the Boronda Center (hereafter, Tresor). The original project engineers provided design plans for each development area and bioswale, and these were used to calculate parking lot areas for use in load calculations. Bioswale designs were also provided for each site. The surface area draining to the Kohl's swale was 53 286 square feet of impervious surface, and the swale consisted of 4683 square feet of landscaping. The main vegetated portion of the swale was approximately 215 feet long and had a flat-bottom, semi-V shape (Supplemental Data, Figure S1). The Chili's swale was constructed similarly and had approximately 2750 square feet of landscaping. The Chili's swale received runoff from approximately 34 900 square feet of impervious surface. The sides of the swales had slopes that did not exceed 50%, and the longitudinal slopes were 1%. The swales, both constructed in 2006, are planted with native bunch grasses in 6 inches of topsoil, which overlays approximately 2.5 feet of compacted subgrade. Water enters from parking areas at multiple points along both sides of the swales (Kohl's; Supplemental Data, Figure S1), infiltrates the vegetated area, and flows through the subgrade to a 4-inch perforated drain. The Boronda Center system conveys water to an adjacent wetland that drains into Santa Rita Creek, then Espinoza Slough, and eventually Moss Landing Harbor and the Monterey Bay.

The Tresor Complex is composed of 7 storm water drainage areas that are comprised of 3 different treatment control classifications. The total impervious surface area of the complex is 173 100 square feet. Two areas drain into bioretention basins constructed in 2011, 1 area drains to a vegetated swale, and 3 areas drain through filter strips; the driveway area is composed of 3800 square feet of impervious surface with no treatment. The area evaluated for the present study was the larger of the 2 bioswale basins, which drains 90 800 square feet of impervious surface (Area 2 draining to BR-2; Supplemental Data, Figure S2). The basin is a depressed vegetated area consisting of porous engineered soils and an underdrain system that captures, treats, and infiltrates runoff.

The bioswale basin is approximately 4000 square feet of vegetation atop 18 inches of soil consisting of topsoil, sand, and compost. Below the soil layer is 2 inches of pea gravel and 6 inches of coarse aggregate gravel. The aggregate layer contains 4-inch diameter perforated PVC spaced at 10-foot intervals in the basin. The Tresor site drains to a municipal storm water system that conveys water directly to the Salinas River and then the Monterey Bay.

Monitoring and analyses

Three storms were monitored for the present study, based on a minimum rainfall of 0.5 inches over 24 h as an indicator of adequate rain. Storm 1 was monitored on 26 February 2014; storm 2 was monitored on 31 October 2014; and storm 3 was monitored from 6 February to 8 February 2015. Prior to each storm, a HOBO™ tipping-bucket digital logger rain gauge (Onset RG3; Onset Computer) was installed at the Boronda Crossing Shopping Center. The rain gauge was attached to a light pole adjacent to the Kohl's site, and this served as an indicator of instantaneous and total rainfall for the 2 Boronda sites. Rainfall data for the Tresor site was taken from the rain gauge at the Salinas Municipal Airport. In addition, mechanical geared pulse flow meters were installed on the outlet drains of each bioswale (Seametrics MJ-R; Seametrics). The meters recorded total flow exiting each bioswale for each storm event.

A central objective of LID is runoff volume control, as reduction in runoff volume is presumed to reduce overall loading of contaminants. During each storm event, the volume of water falling on the catchment area was modeled based on inches of rain recorded by the rain gauges. These data were used to determine the volume entering the treatment system based on parking lot surface area. The volume of water leaving the treatment system was measured as the total flow captured by the flow meters. Infiltration percentage was calculated during the measured portion of each storm by determining the difference between input and output volume. Contaminant loading and load reduction percentage during each storm was calculated using input and output volumes in conjunction with contaminant analytical measurements. Some chemical groups were totaled to simplify load calculations and based on their similar toxic modes of action (e.g., total polynuclear aromatic hydrocarbons [PAHs], total pyrethroids, and total fipronil and degradates).

Using local weather predictions, samples were collected at the beginning, middle, and end of each storm's hydrograph and composited to adequately characterize runoff variability during the storm event. Inflow samples (pre-treatment) from the parking lots to the bioswales were collected by hand and composited in 4-L amber bottles. Inflow samples from the Kohl's and Chili's sites were collected at several curb openings where storm water flowed into the bioswales along the edge of the parking lots. The Tresor inflow samples were collected at the single inflow leading into the bioswale. Composites of 3 outflow samples (post bioswale treatment) were collected from the single outlet conveying discharge from the bottom of each bioswale. All samples were held on ice until the final hydrograph sample was collected, then transported to the laboratory and held in a refrigerator at 4 °C prior to subsampling for chemistry and toxicity testing.

Toxicity tests

Toxicity tests were conducted on all composited inflow and outflow water samples using 3 test species, following modified US Environmental Protection Agency (USEPA) acute test protocols [14]. Storm 1 was tested with the 96-h acute toxicity test with the freshwater cladoceran, *Ceriodaphnia dubia*; the 10-d static renewal test with the freshwater amphipod, *Hyalella azteca*; and the 96-h larval freshwater minnow, *Pimephales promelas*. Acute 96-h tests with *C. dubia* were conducted in 20-mL scintillation vials holding 15 mL of test solution and 5 neonates in each of 5 replicates. Animals were fed a mixture of yeast, cerophyll, trout chow (YCT) and *Selenastrum* 2 h prior to daily 100% renewal of test solution. Final survival in storm water samples was compared with 96-h survival in moderately hard control water. Acute 96-h tests with *P. promelas* were conducted in 500-mL glass beakers holding 250 mL of test solution and 10 larvae in each of 5 replicates. Larval fish were fed newly-hatched *Artemia* nauplii twice daily and test solutions were renewed (80%) at 48 h. Final survival in storm water samples was compared with 96-h survival in moderately hard control water. Tests with amphipods *H. azteca* were conducted in 300-mL glass beaker with 200 mL of test solution and containing 10 animals, 9 d to 15 d old, per replicate (5 replicates). Tests were conducted for 10 d, and 50% of the test solution was renewed every 48 h. Each beaker was fed every 48 h with 1.5 mL of YCT after the renewal. Final survival and growth in storm water samples was compared with 10-d survival and growth in laboratory well water. Growth was measured as dry weight per amphipod at 10 d.

For storms 2 and 3, the 10-d static renewal test with the chironomid (midge) *Chironomus dilutus* was substituted for *P. promelas* because of a lack of toxicity to the fish in storm 1 samples and the relative greater sensitivity of *C. dilutus* to the pesticide fipronil and its degradates [6]. Tests with chironomids were conducted in 300-mL glass beaker with 200 mL of test solution and containing 12 animals (7 d old) in each of 4 replicates. Each test container was supplied with 5 mL of sand as substrate for tube building by the larvae. Tests were conducted for 10 d, and 50% of the test solution was renewed every 48 h. Each beaker was fed daily with an increasing amount of Tetramin slurry (4 g/L), as follows: days 0 to 3, 0.5 mL/d; days 4 to 6, 1.0 mL/d; days 7 to 10, 1.5 mL/d. Final survival and growth in storm water samples was compared with 10-d survival in laboratory well water. Growth of surviving animals was measured as ash-free dry weight.

For all toxicity tests, dissolved oxygen, pH, and conductivity were measured with an Accumet meter and appropriate electrodes (Fisher Scientific). Un-ionized ammonia was measured using a Hach 2010 spectrophotometer (Hach). Hardness and alkalinity were measured at initiation and termination of tests (Hach). Water temperature was recorded with a continuous recording thermometer (Onset Computer Corporation). Additional daily temperatures were measured using a glass spirit thermometer.

Chemistry

All samples were analyzed for the following parameters: total suspended solids, trace metals (USEPA method 200.8 [15]; inductively coupled plasma–mass spectrometry [ICP–MS]), and PAHs (USEPA method 625 [16]). Samples for metals analysis using ICP–MS were preserved in 0.5 N nitric acid prior to analysis on an Agilent 7500 ICP–MS. Samples for PAH analysis were liquid–liquid extracted using methylene chloride, reduced to a 1 mL volume, then analyzed using triple quadrupole gas chromatography–mass spectrometry (GC–MS; Agilent 7890/7000A). The surrogate spike reference compound for PAH analysis was 2-Fluorobiphenyl. The method detection and reporting limits for PAHs were 4 ng/L and 5 ng/L, respectively.

Samples were also analyzed for current-use urban pesticides based on recent urban monitoring in California. These included 9 pyrethroids (USEPA method SW846 8270 modified [17]; bifenthrin, cypermethrin, fenvalerate/esfenvalerate, permethrin, tetramethrin, L-cyhalothrin, cyfluthrin, and allethrin), and fipronil [16] and its degradates (fipronil sulfide, fipronil sulfone, fipronil desulfinyl). Water samples for pyrethroid and fipronil analysis were extracted using USEPA method 3510C [18], which involved a triple liquid–liquid extraction of the storm water samples using methylene chloride, followed by a brief cleanup step. The cartridge cleanup protocol used solid-phase extraction cartridges. The sample extract was loaded onto the cartridge (ENVI-CARB II/PSA; Sigma-Aldrich) stacked on top of an LC-Alumina-a cartridge (Sigma-Aldrich). This was then eluted and the eluate was analyzed with GC–MS using negative chemical ionization on an Agilent 7890A-GC with Agilent 5975 inert XL/EI/CI-MSD equipped with Agilent 7683B autosampler. Esfenvalerate-d6 was used as a surrogate for pyrethroids and fipronil in matrix spikes. The method reporting limits for pyrethroids were from 0.5 ng/L to 1.0 ng/L for all pyrethroids except permethrin (reporting limit = 10 ng/L). The method reporting limit for fipronil and its degradates was 1.0 ng/L. Organophosphate pesticides were not measured, because their use is declining in urban areas in California [19]. Recent monitoring has shown fewer detections of these pesticides [8]. Based on increasing use patterns, the neonicotinoid pesticide imidacloprid was added to the analyses for storms 2 and 3. Samples were extracted using methylene chloride, evaporated, then analyzed using ultra performance liquid chromatography coupled to a triple quadrupole mass spectrometer using electrospray ionization in positive ion mode. Bensulide was used as a reference standard for these analyses. The reporting limit for imidacloprid was 50 ng/L.

Data analysis

Toxicity data was analyzed using the test for significant toxicity to determine statistically significant toxicity [20]. The toxicity of outflow samples was compared with inflow samples using a *t*-test to determine if significant toxicity treatment had occurred. Chemical concentrations were compared with established median lethal concentration (LC50) data for the various toxicity test species and endpoints to determine their potential to cause toxicity (Table 1).

Table 1. Sensitivity of *Hyalella azteca* and *Chironomus dilutus*: LC50s and EC50s used to calculate toxic units (TUs) for selected chemicals detected in storm water

Class	Chemical	*H. azteca*	Endpoint	*C. dilutus*	Endpoint
Pesticides (ng/L)	Bifenthrin	9.3[a]	96-hour LC50	23.0[f]	10-day LC50
	Cyfluthrin	2.3[b]	96-hour LC50	NA	
	L-cyhalothrin	2.3[c]	48-hour EC50	NA	
	Cypermethrin	2.3[c]	96-hour LC50	679[g]	96-hour LC50
	Permethrin	21.1[a]	96-hour LC50	99.0[f]	10-day LC50
	Fipronil	728[d]	96-hour EC50	32.5[d]	96-hour EC50
	Fipronil sulfone	458[d]	96-hour EC50	9.9[d]	96-hour EC50
	Fipronil sulfide	213[d]	96-hour EC50	7.7[d]	96-hour EC50
Metals (μg/L)	Copper	35[e]	10-day LC50	54[e]	10-day LC50
	Zinc	73[e]	10-day LC50	1,125[e]	10-day LC50

[a]Anderson et al. [3].
[b]Weston and Jackson [24].
[c]Maund et al. [39].
[d]Weston and Lydy [6].
[e]Phipps et al. [21].
[f]Ding et al. [40].
[g]Fojut et al. [41].
NA = not applicable.

RESULTS

Quality assurance

Analytical method blanks, laboratory control samples, laboratory control sample duplicates, matrix spikes, and matrix spike duplicates for total suspended solids and metals were all within specified ranges. Method blanks, laboratory control samples, and laboratory control sample duplicates were also within specified ranges for PAH, pyrethroid, and fipronil analytical batches, with the exception of a naphthalene detection in the method blank from storm 3. Matrix interferences were encountered in all PAH, pyrethroid, and fipronil analytical batches, and several matrix spike recoveries were below the acceptable ranges. Several matrix spike duplicates were also outside the acceptable relative percent difference ranges as a result of matrix interferences. It is possible that the concentrations of these chemicals were underestimated. The analytical laboratory determined that the data were still suitable for interpretation based on the results of the laboratory control samples, laboratory control sample duplicates, and method blanks. All toxicity tests met the test acceptability criterion of 90% or greater survival in the control treatments, and all toxicity test water quality parameters were within acceptable limits defined in the test protocols.

Hydrology

Rainfall for the Kohl's and Chili's sites was recorded on site at the Boronda Center, whereas rainfall for the Tresor site was taken from the rain gauge at the Salinas Municipal Airport. Rainfall at the Tresor site, which is approximately 7 km southeast of the other sites, was 48% to 84% less than the rainfall at the Kohl's and Chili's sites (Table 2). Rainfall was measured in hundredth inch increments and used to calculate total volume falling on the drainage area during the sampling period. It was assumed that all water falling on the individual drainage areas entered the bioswales. Discharge meters were removed at the end of the sampling period. Although in some cases the meters were removed before the bioswale had discharged fully, flow at these times was not high enough to register in the meter. For this reason, it was assumed that the remaining water volume was negligible and that the estimated infiltration rates were accurate. Infiltration rates showed minimal variability among storm events and ranged from 83% to 97% (Table 2). Additional descriptions of rain conditions preceding the 3 storms sampled for the present study are provided in the sections *Storm 1*, *Storm 2*, and *Storm 3*.

Results showed consistent reductions of most contaminants by bioswales at the 3 sites during the 3 storm events. In addition, storm water toxicity was detected in each storm event, although toxicity varied by species and was not detected in fish larvae (*P. promelas*) or daphnids (*C. dubia*). Water toxicity to amphipods (*H. azteca*) and chironomids (*C. dilutus*) was reduced by the bioswales.

Storm 1

The bioswales at all 3 sites consistently reduced all of the chemical classes monitored except fipronil and its degradates. Percent reductions of individual chemicals and chemical classes were calculated as the relative percent difference between the input and output concentration at each bioswale. Percent load reductions of each chemical class also were calculated. Percent reductions of total suspended solids ranged from 75% to 100% (Table 3). Very low concentrations of PAHs were detected, and most individual detected PAH concentrations barely exceeded the 0.005 μg/L reporting limit. Reduction of PAHs ranged from 8% to 82%. Reduction of total metals ranged from 47% to 77%. Zinc and copper were the highest in the input samples, and reductions of these metals ranged from 45% to 88%. Two current-use pesticides were detected, bifenthrin and fipronil. Bifenthrin was the only pyrethroid detected during the first storm, and was estimated at concentrations below the reporting limit in the Kohl's and Tresor input samples. The bioswales reduced these concentrations by 100% at Kohl's and 33% at Tresor. Total fipronil (parent compound and degradates) was detected in all samples, but only the estimated concentration of fipronil measured in the Kohl's input was reduced. No fipronil degradates were detected in the Kohl's input or output samples, but fipronil desulfinyl and fipronil sulfone were detected at higher concentrations than the parent compound in the Chili's output and Tresor samples. Fipronil or its degradates were not detected in the Chili's input but 6.1 ng/L of total fipronil was detected in the output sample at this site (Table 3). Similar increases were measured in the Tresor output samples: fipronil desulfinyl increased from 10 ng/L in the input to 12 ng/L in the output, and fipronil sulfone increased from 9.8 ng/L to 12 ng/L (Table 3). The effectiveness of the bioswales to treat fipronil and its degradates was variable and is discussed in more detail in the *Discussion* section. Imidacloprid was not measured in storm 1.

None of the input or output samples from the 3 sites were toxic to larval fathead minnows or to daphnids (Table 4). All of

Table 2. Hydrology results from three storm events

	Monitoring Duration (~h)	Rainfall (in)	Rainfall (gal)	Discharge (gal)	Infiltration (%)
Storm 1					
Kohl's	11.5	0.83	27,570	NA	NA
Chili's	11.5	0.83	18,057	2,840	90
Tresor	12.0	0.64	36,112	1,762	95
Storm 2					
Kohl's	18.5	1.52	50,490	5,248	90
Chili's	19.0	1.52	33,069	5,776	83
Tresor	18.5	1.27	71,602	2,306	97
Storm 3					
Kohl's	46.5	1.20	39,861	5,438	86
Chili's	46.5	1.20	26,102	3,476	87
Tresor	45.5	0.57	32,490	NA	NA

Gallons of rainfall were calculated from inches of rainfall and area of drainage. Discharge measured using mechanical meter.
NA = the discharge was not measured because of gauge malfunction.

Table 3. Percent reduction of concentrations and contaminant loads* of select chemical classes

		TSS				Total Pyrethroids				Total Fipronil				Total Metals				Total PAHs			
		Conc. (mg/L)	% Red.	Load (g)	% Red.	Conc. (ng/L)	% Red.	Load (ug)	% Red.	Conc. (ng/L)	% Red.	Load (ug)	% Red.	Conc. (ug/L)	% Red.	Load (g)	% Red.	Conc. (ug/L)	% Red.	Load (mg)	% Red.
Storm 1																					
Khol's	Inflow	86		8,986		0.50		52.2		0.8		83.6		61.7		6.44		0.06		5.9	
	Outflow	ND	100	NC	NC	ND	100	NC	NC	ND	100	NC	NC	14.0	77	NC	NC	0.01	82	NC	NC
Chili's	Inflow	43		2,943		ND		ND		ND		ND		81.6		5.58		0.10		6.71	
	Outflow	5	88	53.8	98	ND	NC	ND	NC	6.1	NC	65.7	NC	22.0	73	0.24	96	0.03	69	0.32	95
Tresor	Inflow	12		1,642		1.20		164		21.3		2,915		50.6		6.92		0.06		8.08	
	Outflow	3	75	20.0	99	0.80	33	5.34	97	25.3	-19	169	94	25.8	49	0.17	98	0.05	8	0.36	96
Storm 2																					
Khol's	Inflow	136		26,025		30.5		5,836		2.00		383		711		136.2		0.47		89.6	
	Outflow	38	72	756	97	0.4	99	7.96	100	1.10	45	21.9	94	24.8	97	0.49	100	ND	100	0.08	100
Chili's	Inflow	140		17,546		15.9		1,993		1.00		125		276		34.6		0.37		46.7	
	Outflow	12	91	263	99	12	25	263	87	3.40	-240	74.4	41	29.6	89	0.65	98	0.01	99	0.11	100
Tresor	Inflow	93		25,238		169		45,943		18.4		4,993		272		73.7		0.47		128	
	Outflow	20	78	175	99	25.8	85	225	100	11.2	39	97.9	98	42.6	84	0.37	99	ND	100	ND	100
Storm 3																					
Khol's	Inflow	14		2,115		ND		ND		7.80		1,178		123		18.5		0.07		10.0	
	Outflow	10	29	206	90	ND	NA	ND	NC	2.70	65	55.6	95	22.5	82	0.46	97	0.01	85	0.21	98
Chili's	Inflow	102		10,091		ND		ND		5.30		524		196		19.4		0.46		45.0	
	Outflow	ND	100	ND	100	ND	NA	ND	NC	13.8	-160	182	65	25.8	87	0.34	98	0.01	98	0.14	100
Tresor	Inflow	81		9,974		85.7		10,553		43.6		5,369		303		37.3		0.53		65.3	
	Outflow	5	94	NC	NC	ND	100	NC	NC	56.9	-31	NC	NC	19.4	94	NC	NC	0.01	98	NC	NC

*load = concentration × volume (see *Methods* section).
ND = not detected; NC = not calculated.

Table 4. Toxicity and chemistry of bioswale inflows and outflows monitored during three separate storms

						TSS	Bifenthrin	Cyfluthrin	Cypermethrin	(Es)Fenvalerate	Fenpropathrin	L-Cyhalothrin	Permethrin	Fipronil	Fipronil Desulfinyl	Fipronil Sulfide	Fipronil Sulfone	Imidacloprid	Cadmium	Copper	Lead	Nickel	Zinc	Total PAHs
Storm 1		*Hyalella* % Surv.	*Ceriodaphnia* % Survival	*Pimephales* % Survival		mg/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Khol's	Inflow	34	96	95		86	**0.5**	ND	ND	ND	ND	ND	ND	**0.8**	ND	ND	ND	NA	**0.05**	9.6	1	3	48	0.06
	Outflow	**94**	100	93		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA	ND	5.3	0.94	2.1	5.7	0.01
Chili's	Inflow	20	100	98		43	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA	0.13	12	1.9	5.5	62	0.10
	Outflow	**100**	100	88		5	ND	ND	ND	ND	ND	ND	ND	**1**	2.2	ND	2.9	NA	**0.06**	6.5	0.76	2.6	12	0.03
Tresor	Inflow	4	96	95		12	**1.2**	ND	ND	ND	ND	ND	ND	**1.5**	10	ND	9.8	NA	**0.05**	9.7	0.72	3.1	37	0.06
	Outflow	**82**	96	100		3	**0.8**	ND	ND	ND	ND	ND	ND	**1.3**	12	ND	12	NA	ND	5.3	0.75	1.7	18	0.05
Storm 2		*Hyalella* % Surv.	*Ceriodaphnia* % Survival	*Chironomus* % Survival	Dry Wt. (mg)	mg/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Khol's	Inflow	66	100	81	0.39	136	5.6	1.2	3.1	**0.7**	3.6	1.3	15	**0.8**	**0.6**	ND	**0.6**	ND	0.52	78	11	32	590	0.47
	Outflow	**98**	100	71	**0.77**	38	**0.4**	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.1	ND	**0.07**	5.9	1	2.8	15	ND
Chili's	Inflow	72	100	83	0.50	140	7	1	1.6	**1**	4.2	1.1	ND	1	ND	ND	ND	ND	0.22	32	4.2	20	220	0.37
	Outflow	**98**	100	90	**0.87**	12	ND	12	ND	ND	ND	ND	ND	**1.1**	ND	ND	2.3	ND	ND	7.3	1	3.3	18	0.01
Tresor	Inflow	14	100	48	0.17	93	16	1.1	6.2	**0.9**	13	2.1	130	3.3	5.6	ND	9.5	ND	0.2	28	7.4	16	220	0.47
	Outflow	**84**	100	81	**0.96**	20	1.7	ND	**0.4**	ND	1.5	**0.2**	22	2.5	3.6	ND	5.1	ND	ND	5.1	1.2	2.3	34	ND
Storm 3		*Hyalella* % Surv.	*Ceriodaphnia* % Survival	*Chironomus* % Survival	Dry Wt. (mg)	mg/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ng/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Khol's	Inflow	76	92	92	0.78	14	ND	ND	ND	ND	ND	ND	ND	7.8	ND	ND	ND	ND	0.13	15	1.9	6.5	99	0.07
	Outflow	**98**	100	96	**0.87**	10	ND	ND	ND	ND	ND	ND	ND	**1.2**	ND	ND	**1.5**	ND	**0.06**	6.1	1.1	4.2	11	0.01
Chili's	Inflow	100	100	100	0.85	102	ND	ND	ND	ND	ND	ND	ND	5.3	ND	ND	ND	ND	0.14	26	2.3	7.6	160	0.46
	Outflow	96	88	96	0.94	ND	ND	ND	ND	ND	ND	ND	ND	12	ND	ND	**1.8**	ND	ND	3.8	0.68	1.3	20	0.01
Tresor	Inflow	24	96	73	0.81	81	6	ND	6.7	ND	ND	ND	73	24	**4.8**	**2.8**	12	ND	0.22	42	5.3	15	240	0.53
	Outflow	**98**	100	81	1.01	5	ND	ND	ND	ND	ND	ND	ND	32	5.4	2.5	17	ND	ND	4.6	0.34	1.5	13	0.01

TSS = total suspended solids; ND = not detected; NM = not measured.
Bolded toxicity results indicated significant reduction of toxicity in outflow sample. Bolded chemical results indicate estimated concentrations below the laboratory reporting limit.

the input samples were significantly toxic to amphipods and toxicity was significantly reduced by all 3 bioswales. Amphipod survival was 34%, 20%, and 4% in the Kohl's, Chili's and Tresor input samples, respectively, and survival improved to 94%, 100%, and 82% in the output samples of these 3 sites.

No single chemical was measured at concentrations sufficient to account for the toxicity to *H. azteca*. Of the chemicals detected, PAHs, most metals, bifenthrin, and fipronil and its degradates were well below known toxicity thresholds for *H. azteca*. Copper and zinc concentrations were compared with LC50 values, and these metals were within the range that could account for a portion of the toxicity. The copper and zinc LC50s for *H. azteca* from Table 1 are 35 μg/L and 73 μg/L, respectively [21]. For illustration, toxic units (TUs) were calculated for the input and output samples by dividing the copper and zinc LC50 values for *H. azteca* by the measured concentrations. Assuming additive toxicity of these metals [22], the total copper + zinc TUs for *H. azteca* in the Kohl's input was 0.93 TUs and the total copper and zinc TUs in the Kohl's output was 0.23. Copper + zinc TUs in the Chili's input and output were 1.2 and 0.35, respectively, and copper + zinc TUs in the Tresor input and output were 0.79 and 0.39, respectively. In all cases, the TUs were largely accounted for by zinc, which is considerably more toxic to *H. azteca* (LC50 = 73 μg/L) than to *C. dubia* (LC50 = 360 μg/L), which might also explain why no toxicity to *C. dubia* was observed.

The highest concentration of the pyrethroid pesticide bifenthrin was measured in the Tresor input sample; and although this may have accounted for some of the toxicity in this sample (TU = 0.16), the concentration was below the laboratory reporting limit, and therefore estimated. It should also be noted that recovery of the deuterated esfenvalerate analyzed as a pyrethroid surrogate was low in the GC–MS analysis of these samples as a result of matrix interference (51–53%), and the pyrethroid concentrations in these analyses likely under-represent the true concentrations in these samples.

Storm 2

As was observed in storm 1, the bioswales at all 3 sites reduced all of the chemicals monitored in storm 2, except for cyfluthrin in the Chili's outflow, and fipronil, whose treatment was variable. The reduction percentages of total suspended solids ranged from 72% to 91% (Table 3). Concentrations of PAHs were very low, and few individual compounds exceeded the 0.005 μg/L reporting limit when they were detected. Reduction of these low concentrations of PAHs ranged from 99% to 100%. All metals were reduced in the output samples. Of the metals measured, zinc and copper were the highest in the input samples, and zinc concentrations were considerably higher in the storm 2 input samples. The reduction percentages of zinc ranged from 85% to 97%, and reductions of copper ranged from 77% to 92% (Table 4). Several of the pyrethroid pesticides were detected in the input samples and reduced in the outputs. Total pyrethroid concentrations had a high percentage reduction at Kohl's and Tresor (99% and 85%, respectively), but only 25% reduction at Chili's due to the concentration of cyfluthrin detected in the output sample. Potentially toxic concentrations of bifenthrin, cypermethrin, lambda-cyhalothrin, and permethrin were detected in the input samples, and were reduced to concentrations below the *H. azteca* LC50s in the output samples in all but 1 case (permethrin at Tresor, Table 4). As an example, bifenthrin was detected at concentrations toxic to *H. azteca* in the Kohl's, Chili's, and Tresor input samples and was reduced by 93%, 100%, and 89%, respectively, in the output samples at these sites. The pyrethroid pesticide cyfluthrin increased from 1 ng/L in the Chili's inflow to 12 ng/L in the Chili's outflow. Possible reasons for this increase are provide in the *Discussion* section

Total fipronil was detected in all input samples and was reduced by 45% and 39% in the output samples of Kohl's and Tresor, respectively. Total fipronil increased in the Chili's output by 2.4 times (Table 3). Fipronil desulfinyl and fipronil sulfone were detected in the Kohl's input samples. Fipronil desulfinyl was reduced 100% in the Kohl's output sample, whereas the sulfone degradate increased by 45%. The sulfone degradate increased by 100% in the Chili's output sample. The fipronil desulfinyl and sulfone degradates decreased by 36% and 46%, respectively, in the Tresor output samples (Table 4). Possible reasons for the variable treatment of fipronil are discussed in more detail in the *Discussion* section. Imidacloprid was not detected in any samples from storm 2.

None of the input or output samples from the 3 sites were toxic to daphnids (Table 4). All of the input samples were significantly toxic to amphipods and all toxicity was significantly reduced by the bioswales. Amphipod survival rates were 66%, 72%, and 14% in the Kohl's, Chili's, and Tresor input samples, respectively, and survival improved to 98%, 98%, and 84% in the output samples of these 3 sites. Based on the toxicity and chemistry results from storm 1, the 10-d growth and survival test with *Chironomus dilutus* was substituted for the larval fish test with *P. promelas*. Statistically significant toxicity to *C. dilutus* survival was observed in both the Kohl's and Tresor input and output samples, but not in the Chili's samples. Significant reductions in *C. dilutus* weight were observed in the Kohl's and Tresor input samples, and growth significantly improved by 49% and 82%, respectively, in the output samples from these 2 sites. Although not statistically significant, a reduction in *C. dilutus* weight was also observed in the Chili's input sample and improved by 43% in the output sample (Table 4).

Several pyrethroids were measured at concentrations sufficient to account for the toxicity to *H. azteca*. All storm 2 input samples contained at least 0.5 TUs of bifenthrin, and these were reduced below toxic thresholds in the output samples. In addition, potentially toxic concentrations of cypermethrin and permethrin were detected in the Kohl's and Tresor input samples. Pyrethroid toxicity is additive [23]; therefore, this characteristic likely also played a role in amphipod mortality in these input samples. The 12 ng/L of cyfluthrin measured in the Chili's outflow was sufficient to cause toxicity, yet this sample was not toxic to *H. azteca*. Based on the LC50 of 2.3 ng/L [24], there were 5.2 TUs of cyfluthrin in the outflow sample. The reason for the lack of toxicity in this sample is unclear.

As in storm 1, copper and zinc were measured at potentially toxic concentrations at all 3 sites. For example, 8 TUs, 3 TUs, and 3 TUs of zinc were measured in the input samples at Kohl's, Chili's, and Tresor, respectively [21]. Of the other chemicals detected, PAHs, all other metals, and fipronil and its degradates were well below known toxicity thresholds for *H. azteca*.

Toxicity to *C. dilutus* in storm 2 was also likely attributable to mixtures. For example, based on LC50s for pyrethroid toxicity to *C. dilutus*, the Tresor input sample contained 1.3 TUs of permethrin and 0.7 TUs of bifenthrin. This sample also contained 0.96 TUs of fipronil sulfone [6]. It is also possible concentrations of copper and zinc played a role in toxicity to *C. dilutus* in the input samples. As noted, there was a significant reduction in *C. dilutus* growth in the Kohl's and Tresor input samples, and growth significantly improved in all output samples. Based on 10-d water mortality LC50s, [21] and assuming there is a relationship between copper effects on midge 10-d survival and growth, there were 1.44 TUs, 0.59 TUs, and 0.52 TUs of copper in the Kohl's, Chili's, and Tresor input samples, respectively. These were reduced to 0.11 TUs, 0.14 TUs, and 0.09 TUs in the output samples at Kohl's, Chili's, and Tresor, respectively.

Storm 3

As was observed in storms 1 and 2, the bioswales at all 3 sites reduced all of the chemicals monitored except fipronil during storm 3. The reduction percentages of total suspended solids ranged from 29% to 100% (Table 3). As in previous storms, only very low concentrations of individual PAHs were detected, and total PAHs were reduced by 85% to 98% (Table 3). Total metal concentrations were reduced by 82% to 94% in the output samples. Zinc and copper continued to be the metals with the highest measured concentrations. The reduction percentages of zinc ranged from 88% to 95%, whereas reduction percentages of copper ranged from 59% to 89%. No pyrethroid pesticides were detected in the Kohl's and Chili's samples; however, 3 pyrethroids were detected in the input samples at Tresor. Bifenthrin, cypermethrin, and permethrin were detected at toxicologically relevant concentrations in the Tresor input samples and were completely removed by the Tresor bioswale (Tables 3 and 4). Total fipronil was detected in all input samples but was reduced only in the Kohl's output. Fipronil compounds increased in the Chili's and Tresor outputs relative to their inputs (Table 4). Fipronil sulfone increased in all output samples, relative to the inputs. Fipronil desulfinyl and fipronil sulfide were detected at Tresor, and neither if these were affected by this bioswale. Imidacloprid was not detected in any of the samples from storm 3.

None of the input or output samples from the 3 sites were toxic to daphnids (Table 4). The Kohl's and Tresor input samples were significantly toxic to amphipods, and toxicity was significantly reduced by the bioswales. Amphipod survival was 76% and 24% in the Kohl's and Tresor input samples, respectively, and survival improved to 98% in both output samples. Statistically reduced survival of *C. dilutus* was observed in the Tresor input sample (73%), and survival improved to 81% in the output sample. Although growth was lower in all input samples, and higher in all outputs, no statistically significant reductions in *C. dilutus* weight were observed.

Three pyrethroids were measured at concentrations sufficient to account for the toxicity to *H. azteca* mortality in the Tresor input, which was the most toxic sample during this storm. The Tresor input samples contained 0.78 TUs of bifenthrin, 2.9 TUs of cypermethrin [24], and 3.6 TUs of permethrin [25], and additive toxicity likely played a role in amphipod mortality in these input samples. As in the previous storms, copper and zinc were measured at potentially toxic concentrations at all 3 sites. For example, 1.4 TUs, 2.2 TUs, and 3.3 TUs of zinc were measured in the input samples at Kohl's, Chili's, and Tresor, respectively [21]. Of these 3, Chili's was not toxic to amphipods. Of the other chemicals detected, PAHs, all other metals, and fipronil and its degradates were well below known toxicity thresholds for *H. azteca*.

Moderate toxicity of the Tresor input to *C. dilutus* in storm 3 also could have been attributable to pyrethroid mixtures. For example, based on 10-d LC50s for pyrethroid toxicity to *C. dilutus*, the Tresor input sample contained 0.74 TUs of permethrin and 0.26 TUs of bifenthrin. This sample also contained 6.7 ng/L cypermethrin (LC50 = 679), thus, additive toxicity caused by all 3 pyrethroids could have played a role in the observed effects on midges.

Contaminant loading

Final contaminant loads for the Kohl's site during storm 1 and the Tresor site during storm 3 could not be calculated because of either malfunctioning flow gauges (Kohl's) or extremely low flows that bypassed the gauge (Tresor). Some percent reductions of loads could not be calculated because chemical classes were not detected in the input sample. Because of high infiltration rates (83–97%; Table 2), all reduction percentages in chemical loading exceeded 87%, except for fipronil and its degradates (Table 3). Although total fipronil concentrations were sometimes measured at higher concentrations in the output sample, the overall load of total fipronil was reduced from 41% to 98%. In a single case, storm 1 at Chili's, initial load was not calculated because no fipronil was detected in the input sample.

DISCUSSION

As water conservation efforts increase in California, incorporation of green infrastructure is gaining acceptance as a preferred approach to treat and retain storm water. The State Water Resources Control Board and its 9 regional boards are requiring best management practices associated with LID design principles be incorporated into new development and redevelopment projects. Low impact development best management practices designed to reduce contaminant loading to surface water include vegetated buffers on roadways, raingardens for roof runoff, and vegetated bioswales for parking lot runoff. Studies of the efficacy of these systems to improve runoff water quality have largely focused on conventional contaminants. Several studies have discussed reductions by bioswales of total suspended solids, PAHs/total petroleum hydrocarbons, nutrients [26,27] and heavy metals (W. Groves, 1999, Masters thesis, University of California, Santa Barbara, CA, USA). Few studies have measured current-use pesticides, and fewer still have measured the effects of bioswales on the toxicity of storm water. McIntyre et al. [12] recently demonstrated that experimental soil bioretention columns reduced toxicity of storm water to developing zebra fish embryos, likely through reductions of PAHs. In related studies, the soil bioretention columns also eliminated storm water toxicity to adult coho salmon [13] and reduced storm water toxicity to juvenile salmon and 2 invertebrates: *Ceriodaphnia dubia* and baetid mayfly nymphs [11]. In addition to measures of total suspended solids, metals, and PAHs reported in previous studies, the present study emphasized toxicity reductions using species demonstrated to be sensitive to current-use pesticides, such as pyrethroids and fipronil. These measures are particularly relevant because surface water toxicity to invertebrates is commonly detected in California, and many recent studies have shown that toxicity to invertebrates is now associated with these pesticides [1,5,6,8].

The efficacy of the 3 parking lot bioswales to treat total suspended solids, metals, and PAHs were comparable to previous findings reported for these constituents. For example, the average reductions of copper and zinc during the 3 storms for all 3 bioswales were 70% and 85%, respectively. A 2003 summary report by the Oregon Department of Environmental Quality [10] reported average reductions of copper and zinc compiled from numerous bioswale studies were 46% and 63%. McIntyre et al. [12] reported reductions of 72% and 99% for copper and zinc, respectively, using a soil bioretention column as a bioswale analog. The average reduction of total suspended solids by all bioswales in the present study was 79%, comparable to the range of 83% to 92% reported by Oregon Department of Environmental Quality [10]. McIntyre et al. [12] reported a total suspended solids reduction of 72%. In the present study, PAH concentrations were generally low and were reduced by greater than 98% in all bioswale effluents during the 3 storms. McIntyre et al. [12] also reported a 98% reduction of total PAHs.

The goal of the USEPA is to retain rainfall on site via infiltration, evaporation, and transpiration and to reuse water "to the same extent as occurred prior to development" [28]. The primary mechanism of volume reduction in bioswales is infiltration. Previous studies have reported a wide range of infiltration performance in storm water bioswales, and results are based on several factors, including soil type, design specifications, rainfall volumes, and construction methods. It is also possible that the bioswale effectiveness varies over time, but this subject has not been well studied. The Boronda Shopping Mall bioswales were approximately 8 yr old at the time of the present study, and the Tresor bioswale was approximately 3 yr old. The International Stormwater Best Management Practice Database provides an evaluation of volume reduction for 13 bioswales and determined the average rate of infiltration was 48% [29]. A study by Rushton [30] found that the installation of parking lot swales resulted in 30% less runoff, but studies of swales adjacent to roadways have shown volume reductions ranging from 9% to 100% [31–33].

Volume reduction in the present study was measured as percent infiltration and ranged from 83% to 97%. The estimated rates were on the higher side of the range in previously published results, likely because of the assumptions described in the *Hydrology* section. It was assumed that all rainfall in the drainage areas entered the bioswales, and it was assumed that any water remaining in the swale after the removal of the flow gauge was negligible. It should also be noted that the flow gauges had a minimum working flow rate of 0.22 gallon/min. It was likely that some unrecorded low flows passed through the gauges at the beginning and end of the rain events.

Our results indicated that the effectiveness of the bioswales to treat current-use pesticides varied depending on the pesticide. Seven pyrethroid pesticides were detected during the present study, and these were all effectively removed by the bioswales, except in 1 case. Cyfluthrin increased from 1 ng/L in the Chili's inflow to 12 ng/L in the Chili's outflow in storm 2 (Table 4). Bifenthrin was detected in 6 of the 9 inflow samples and in all cases but the storm 1 outflow sample at Chili's (33% reduction), the reduction of the bifenthrin concentration in the outflow was 89% or greater. The average reduction of bifenthrin by all bioswales was 86%. Fipronil was the other commonly detected current-use pesticide, and in contrast to pyrethroids, treatment of this pesticide was highly variable. In 6 of 9 samples, concentrations of fipronil or its degradates increased in the outflow samples relative to the inputs. This occurred in the Chili's output in storm 1, the Kohl's and Chili's outputs in storm 2, and all 3 outputs in storm 3. It is possible the variable treatment of fipronil by the bioswales is related to its more moderate solubility. Fipronil has an octanol–water partition coefficient ($\log K_{OW}$) of 4.0 and therefore is considerably more soluble than bifenthrin ($\log K_{OW} = 6$). In 6 cases, fipronil or 1 of its degradates was detected in outflows where none was detected in the inflow. The reason for this is not clear but could have been attributable to residual pesticide bound in the bioswales and remobilized with storm water. Other research has shown that fipronil and its degradates were not effectively removed from process streams during conventional wastewater treatment but that wetland treatment removed 44% and 47% of fipronil and its degradates, respectively [34]. All other contaminants monitored in the present study were reduced by the bioswales, except for the case of cyfluthrin, as noted in the Chili's outflow during storm 2. We have no explanation for the increase in cyfluthrin in this instance.

Storm 2 had the greatest number of detections and highest measured concentrations of current-use pesticides (Table 2). Whereas all 3 of the storms monitored occurred during a period of record drought in California, storm 2 was preceded by the longest dry period during the study (5 mo) and is better described as a "first flush" event than the other 2 storms. Approximately 1.2 inches of rain were measured in the 25 d preceding storm 1; furthermore, although no measurable rain had occurred in the 44 d preceding storm 3, 1.2 inch had fallen from 15 December to 17 December 2013. For the most part, the runoff from storm 2 contained the highest loadings of all chemical classes.

California does not require records of residential applications of pesticides, so it is not possible to compare the relative application rates of pesticides at the 3 sites. However, the data suggest there were differences in pesticide use patterns. The greatest concentrations and detections of current-use pesticides were measured in the inflow to the Tresor bioswale, particularly in storms 2 and 3. Unlike the Kohl's and Chili's sites, which are surrounded by parking lots that service department stores, the Tresor site is surrounded by residential apartments.

Organophosphate pesticides were not analyzed in the present study because their urban use has declined since the USEPA canceled many urban applications for diazinon and chlorpyrifos in 2005 [18]. Therefore, we prioritized the pyrethroid and fipronil class of pesticides, which have replaced the organophosphates to a large extent. Lack of toxicity to *C. dubia* in the present study supports the assumption that organophosphate pesticides would be less likely to be detected because *C. dubia* is highly sensitive to diazinon and chlorpyrifos, 2 of the organophosphate pesticides most commonly detected in past monitoring studies in California [1]. We also measured the neonicotinoid pesticide imidacloprid in samples from storms 2 and 3, because recent evidence shows neonicotinoid use and detections are increasing in California, particularly in agricultural watersheds [35]. Imidacloprid was below the detection limit in all samples, although a trace level of this pesticide was detected in the Kohl's input sample from storm 2 (data not shown). Starner and Goh [35] suggested that urban use of neonicotinoids is increasing in California; as such, future storm water monitoring should consider this class of pesticides in urban and agricultural settings. Given their high solubility, relative persistence, and high toxicity to aquatic insects [36], this class of pesticide may be particularly problematic to treat using traditional LID best management practices.

Reductions of chemicals were measured as percent concentration reduction, which can be related to associated toxicity, and percent load reduction, which relates to mass loading. Load reductions largely came from volume retention through infiltration. For example, the percent concentration reductions for total suspended solids ranged from 29% to 100%, but percent load reductions ranged from 90% to 100%. The International Stormwater Best Management Practices Database evaluated 23 biofilter studies employing grass swales and determined the median concentration reduction percentage of total suspended solids was only 22% [29]. The concentration ranges in the evaluated studies were comparable to those found in the present study. Caltrans [37] evaluated several highway biofiltration swales and determined an average 49% concentration reduction for total suspended solids but an average load reduction of 76%. Similar results were observed for the other chemical classes in the present study. Percent concentration reductions for pyrethroids, metals, and PAHs ranged from 8% to 100%, but percent load reductions ranged from 87% to 100%. The Best Management Practices Database evaluated 16 bioswale studies for copper reduction and found a median concentration reduction of only 14% [29]. The Caltrans bioswales were able to reduce copper concentrations by an average of 63% and copper loading by an average of 82% [37]. Although total fipronil concentrations were not always reduced, loading of total fipronil was reduced by 41% to 98% because of volume reduction.

The toxicity test results demonstrated that bioswales are effective at removing surface water toxicity from parking lot runoff. All but 1 of the inflow samples were significantly toxic to amphipod survival, and the storm water was reduced to nontoxic levels in all outflow samples except the Tresor outflow in storm 1. Amphipod survival in the storm 1 Tresor outflow was 82%, which was significantly lower than the control survival but a 96% increase over the inflow survival (4%). The Kohl's and Tresor inflow samples were also toxic to *C. dilutus* survival and growth in storm 2 (not tested in storm 1), and the Tresor inflow was toxic to *C. dilutus* survival in storm 3. Toxicity to *C. dilutus* was reduced in the corresponding outflow samples in storms 2 and 3, except for survival in the Kohl's outflow in storm 2. In contrast to these 2 species, none of the inflow samples were toxic to *C. dubia* in the 3 storms, and no sample was toxic to fish larvae in storm 1 (*P. promelas*). The pattern of increased toxicity to amphipods and midge larvae but not daphnids or fish larvae confirms a recent trend observed in California surface water toxicity monitoring that has occurred as organophosphate pesticides have been replaced by pyrethroids, and more recently by fipronil [1,6]. Data from the present study also suggested that zinc and copper could have played a role in the toxicity of the storm water based on TU analyses, but this could not be confirmed without conducting toxicity identification evaluations, which was beyond the scope of the present study.

The results illustrate the fact that species and endpoints used for toxicity monitoring should be selected based on their relative sensitivity to contaminants of concern. Amphipods and chironomids were more responsive to the contaminant mixtures in the present study. Although daphnid neonates and fish larvae were apparently not sensitive to chemicals in the parking lot runoff, fish embryo development has recently been shown to be sensitive to PAHs in storm water [12], and chemical mixtures in storm water have been shown to be lethal to adult coho salmon [13]. In addition, Skinner et al. [38] showed that development of silverside embryos was inhibited by metals in storm water. These studies suggest that fish embryo–larval development may be a more appropriate indicator of the toxicity potential of storm water constituents than larval growth and survival. Adult coho salmon mortality associated with first flush storm events is apparently related to their unique sensitivity to the complex mixture of contaminants in highway runoff in Pacific Northwest urban streams [13].

The results of the present study demonstrate the utility of including toxicity tests as a means of evaluating the effectiveness of green infrastructure best management practices to treat complex mixtures of chemicals in storm water. As new construction incorporates LID practices to treat runoff, it will be informative to monitor the effectiveness of these designs to verify protection of receiving systems. As new contaminants of concern are identified in surface waters, the suite of toxicity test indicators should evolve to incorporate appropriate species and endpoints.

Supplemental Data—The Supplemental Data are available on the Wiley Online Library at DOI: 10.1002/etc.3472.

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Data availability—Data are available upon request from the corresponding author at anderson@ucdavis.edu. The file repository is Salinas LTD.

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