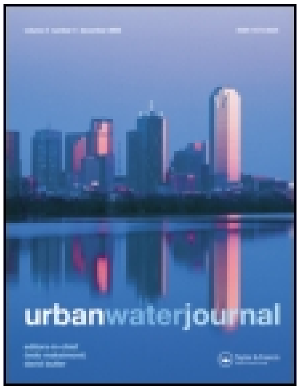

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RESEARCH ARTICLE

Performance of engineered soil and trees in a parking lot bioswale

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A bioswale integrating an engineered soil and trees was installed in a parking lot to evaluate its ability to reduce storm runoff, pollutant loading, and support tree growth. The adjacent control and treatment sites each received runoff from eight parking spaces and were identical except that there was no bioswale for the control site. A tree was planted at both sites. Storm runoff, pollutant loading, and tree growth were measured. There were 50 storm events with a total precipitation of 563.8 mm during February 2007 and October 2008. The bioswale reduced runoff by 88.8% and total pollutant loading by 95.4%. The engineered soil provided a better aeration and drainage for tree growth than did the control's compacted urban soil. The superior performance of the bioswale demonstrated its potential use for large-scale application in parking lots and roadsides to reduce runoff and support tree growth.

Keywords: urban runoff; water quality; engineered soil; bioswale; parking lot

Introduction

Increasing urbanisation has resulted in the construction of more roads and parking lots, significantly increasing the amount of impervious land cover in our towns and cities (Arnold and Gibbons 1996). Davis *et al.* found parking lots accounted for 5% of urban land use in the Upper Great Lakes region and 7% of the total urban area in Tippecanoe, Indiana (Davis *et al.* 2010a, 2010b). In metropolitan Sacramento, parking lots make up 12% of the urban land (Akbari *et al.* 2003). Impervious land cover alters the quantity and quality of surface runoff because of its effects on surface retention storage, rainfall interception, infiltration, runoff temperature, and contaminants. Large volumes of excess storm water runoff from urbanised areas cause flooding, water pollution, groundwater recharge deficits, destroyed habitat, beach closures, and toxicity to aquatic organisms (Greenstein *et al.* 2004, USEPA 2005). Runoff from parking lots has unique flushing effects (Black 1980) and can have significant ecological impact. Best Management Practices (BMPs) have been developed to reduce parking lot runoff and pollutant loading. These BMPs include onsite treatments such as sand filters (USEPA 1999b), permeable pavement (Booth and Leavitt 1999), low-impact parking lot designs (Rushton 2001), and other types of treatment systems (Sonstrom *et al.* 2002). These decentralised BMPs used source-control approaches with potential to significantly reduce urban stormwater runoff quantity (Shuster *et al.* 2008). Vegetative swales are recommended by the USEPA as BMPs to clean pollutants and improve water quality (Barrett *et al.* 1998, Cheng 2003, Vyslouzilova *et al.* 2003, USEPA 2004, Matteo *et al.* 2006, Liu *et al.* 2007). Vegetation reduces surface runoff by canopy interception (Xiao *et al.* 2000a) and improves infiltration of compacted subsoil (Bartens *et al.* 2008). Some of the intercepted rainwater will never reach the ground surface to produce surface runoff. Increasing canopy cover is one approach to reducing surface runoff. Indeed, there are municipal stormwater credit programs in several US cities that promote tree planting and conservation (Greensboro 1996, Haubner *et al.* 2001, City of San Jose 2006, City of Austin 2007, City of Portland 2008, City of Seattle 2008). For example, The City of San Jose, California has a program that gives credits for new trees planted within 9.1 m of impervious surfaces and for existing trees kept on a site if the trees' canopies are within 6.1 m of impervious surfaces. The credit for each new deciduous tree is 9.3 m^2, and the credit for each new evergreen tree is 18.6 m^2. The credit for existing trees is the square-footage equal to one-half of the existing tree canopy. Up to 25% of a

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site's impervious surface area can be treated through the use of trees.

Impervious land cover not only causes environmental problems downstream but also creates many problems that affect our daily quality of life. Urban heat islands (Swaid and Hoffman 1989, Taha *et al.* 1991, Simpson *et al.* 1993) and air quality problems (Smith 1978, McPherson and Simpson 1999, Scott *et al.* 1999, Simpson *et al.* 1999, Nowak *et al.* 2000) are directly caused by impervious land cover and the lack of vegetation cover. Tree planting programs have been established in many cities across the United States (such as Denver, CO, Los Angeles and Sacramento, CA, and New York, NY etc.) to improve urban air quality and reduce the urban heat island (Hickenlooper 2008, Sacramento Tree Foundation 2008, McPherson *et al.* 2010). Many cities in California have established parking lot ordinances that require 50% of paved area shaded within 10 to 15 years (McPherson 2001) and treatment for 85th percentile 24-hour runoff event (California State and Regional Water Quality Control Boards 2008). However, actual shading is often less than required. One reason is stunted tree growth due to inadequate soil volume, drainage, and aeration. Polluted urban stormwater runoff eventually builds up pollutants in surface soils and sub-surface sediments to cause environmental problems, including groundwater contamination (Mikkelsen *et al.* 1997) and the growing risk of heavy metal uptake by humans and livestock (Camobreco *et al.* 1996, Moller *et al.* 2005).

Recently, green infrastructure technology (Bartens *et al.* 2008, Day and Dickinson, 2008, Bartens *et al.* 2009) or biofilters (Bratieres *et al.* 2008, Blecken *et al.* 2009, Hatt *et al.* 2009) has integrated engineered soil and vegetation to treat and store parking lot surface runoff. Engineered soil, a mixture of stones and regular soil, is friendly to trees in urban environments because it is more porous than native backfill urban soil (Costello and Jones 2003, Smiley *et al.* 2006). Indeed, engineered soil has been used for landfill gas treatment in Australia (Dever *et al.* 2007) and the United States (City of Santa Rosa 2010, Clearlake Lava Inc. 2010). The highly porous, engineered soil provides space for temporarily storing surface runoff (Day and Dickinson 2008, Thompson *et al.* 2008, Xiao and McPherson 2008). By promoting deeper growing roots, engineered soil reduces the heaving of sidewalks, curbs and gutters by tree roots (Grabosky and Bassuk, 1995, Grabosky and Bassuk 1996, Smiley *et al.* 2006).

Bioswales, a part of landscape elements, have been designed to remove pollution from surface runoff. Traditional, the swales consist of a swaled drainage course filled with vegetation, compost and/or riprap. As part of surface runoff flow path, it is designed to maximise the time water spends in the swale, which aids the trapping of pollutants (USEPA 1999a). Biological factors also contribute to the breakdown of certain pollutants.

The engineered soil used in this study offers several advantages over other engineered soils. It is made of natural materials (75% lava rock and 25% loam soil, porosity: 45.3%) that are readily and inexpensively available in California. Because the main structural element is lava rock, the soil is very porous with high water storage capacity, so it stores more stormwater and makes more water available to the trees. The lava rock has a very high surface area to volume ratio, with nooks and crannies that trap pollutants and foster growth of bacteria that decompose nutrient pollutants (Xiao and McPherson 2008). Reducing surface runoff reduces pollutants travelling downstream into the receiving water body. The potential of this engineered soil system was tested in laboratory experiments (Xiao *et al.* 2006). The purpose of this study was to evaluate its effectiveness in the field. In this study a bioswale was constructed adjacent to an existing parking lot. The objective was to evaluate its performance in terms of pollutant removal rate, storm-runoff reduction capacity, and tree growth.

Methods

Study site

The study site was located at the University of California Davis (UCD) campus (Davis, California, 121°46′32″W, 38°32′09″N). The campus is located in the heart of the Central Valley, between the Coast Range to the west and the Sierra Nevada to the east. The climate is Mediterranean, summers are sunny, hot, and dry while winters are wet but not cold, it rarely snows. On average, 90% of the average annual precipitation 446.0 mm occurs between November and April. Moisture comes from the southern side of the study site (i.e. Pacific Ocean) owing to the influence of mountain ranges. The Sierra Nevada Mountain Range blocks moisture from the east. The soils of the study region are varied from loamy soils to heavy clay soils. The study site was in the southwest corner of parking lot 47A at the intersection of La Rue Drive and Dairy Road (Figure 1). The micro-topography of the parking lot was elevated and slightly sloped toward north and south sides for drainage. Runoff from the south side of the lot drained into the peripheral landscape along La Rue Drive, with overflow draining into the street. The adjacent treatment and the control sites had exactly the same dimensions. The study site provided parking for dormitory residents from the project's inception in February, 2007 until June 2008 when the entire parking lot became a staging area for a

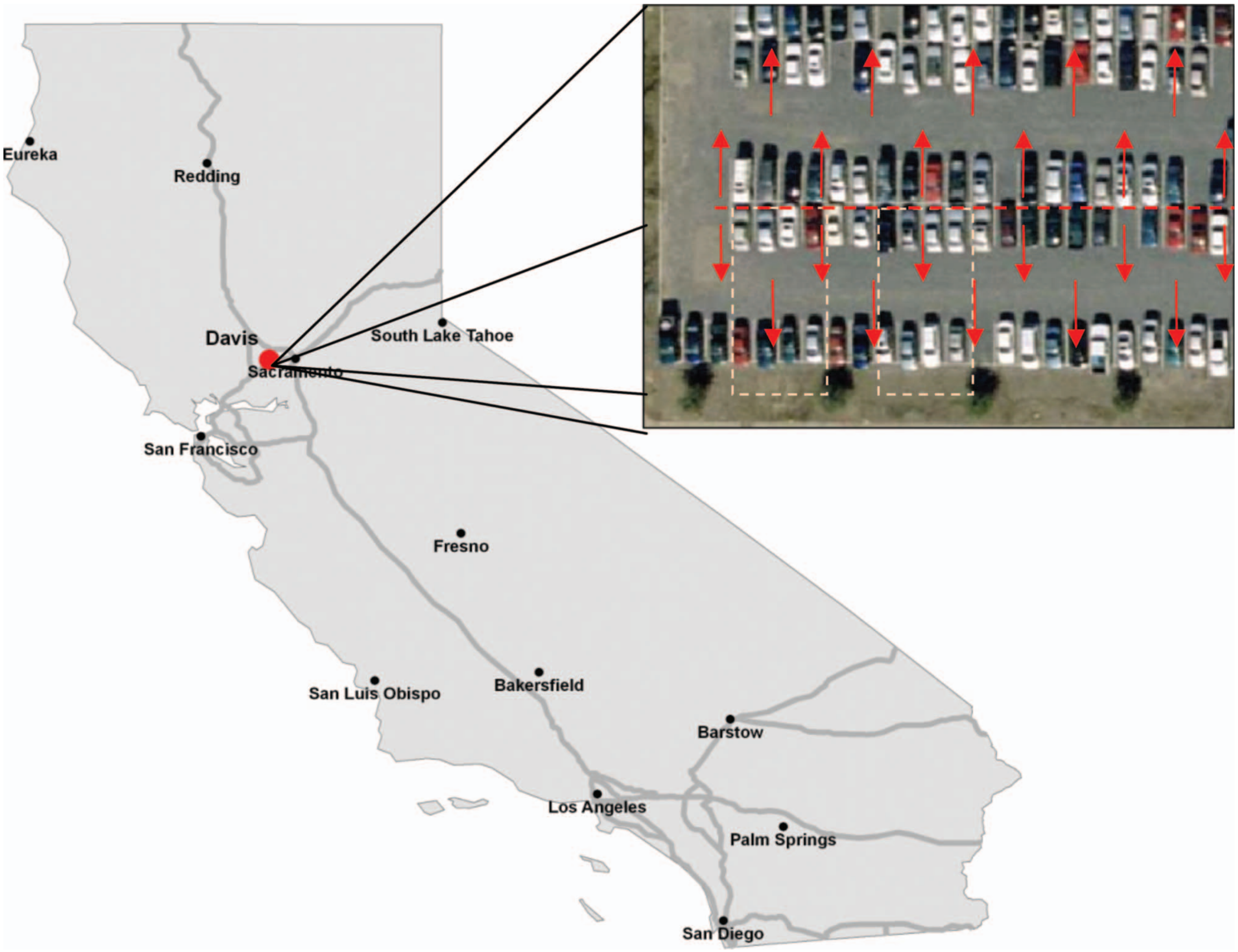

Figure 1. The study sites are outlined with dash line in the images (2003,WAC Corporation, Inc. Eugene, Oregon, USA). Surface drainage of the parking lot is shown with the arrow line.

nearby campus construction project. There were neither lockup shed nor structures built in this parking lot that may change the runoff collection area. From June to October 2008, when the study concluded, the construction and other structures near the site did not influence stormwater runoff patterns or volumes.

Experiment setup

A treatment site (10.4 m × 17.4 m) included eight parking spaces and a buffer strip (0.6 m × 10.4 m) between the parking spaces and the bioswale. The bioswale was 10.4 m long, 2.4 m wide, and 0.9 m deep. The treatment site had a rectangular shape. The north edge of the treatment site was the ridge of the parking lot where surface runoff was naturally divided to flow either to the north or the south. Two pieces of rope (17.4 m long, 1.0 cm diameter) covered by tar (17.8 cm wide and 1.9 cm deep) were placed on the east and west edges of the treatment site on the parking lot to prevent water from flowing across and off treatment site. Three redwood boards (5.1 cm × 25.4 cm) were buried on the west, south, and east edges of the bioswale. These boards were set 2.5 cm above ground surface. The redwood boards along the east and west sides of the bioswale were extended to the edge of the parking lot where they met the ropes. The three boards and the two rope/tar strips defined the boundaries of the treatment site. Approximately 28.3 m^3 of native soil was excavated and replaced with engineered soil to form the base of the bioswale. A fine graded non-woven geotextile (filter fabric Mirafi 180N, TenCate, Pendergrass, GA 30567) was placed at the bottom, sides, and top of the engineered soil. The geotextile prevented fine soil/sediment from entering the system and reducing the system's porosity. During soil replacement, the engineered soil was packed with a tamping rammer (Mikasa Sangyo Co., Ltd., Model:

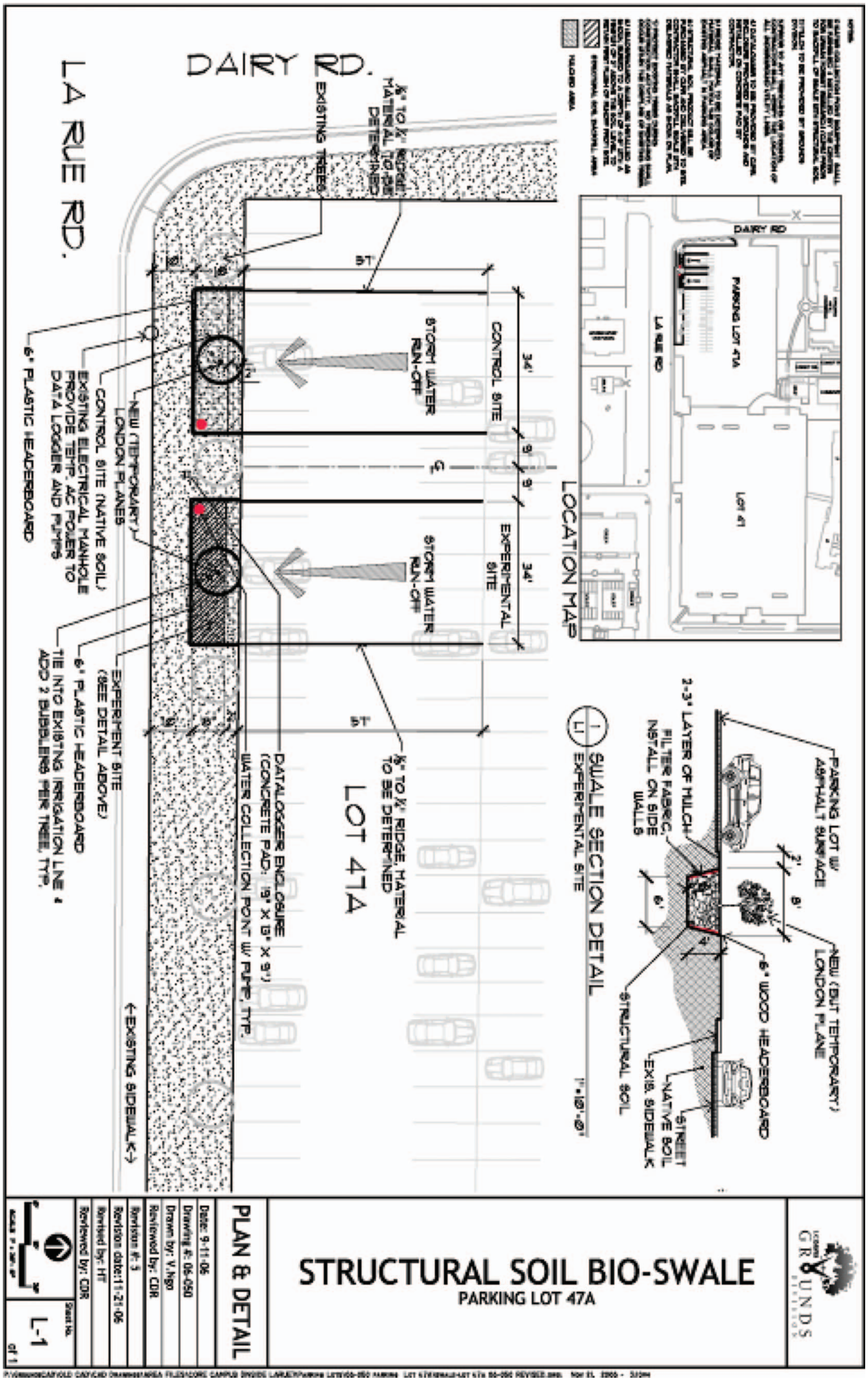

Figure 2. Detail field experiment setup design.

Figure 3. Field installation. Photos were taken at different stage of the field installation. a) Before the bioswale installation, b) excavated pit, c) filled with engineered soil, d) compacted the soil, e) leveled the pit, f) tested the soil settlement, g) added tree to the system, h) finished site, i) both control and treatment sites were coved with mulch to match the surrounding land cover.

MT-65H). A 19.0)litre Bloodgood London Plane (*Platanus x acerifolia 'Bloodgood'*) tree was planted in the centre of the bioswale. Initially, the bioswale was designed to be 1.2 m deep, but was reduced to 0.9 m depth during field installation to avoid damaging utility and communication cables that were underground.

The control site had an identical setup as the treatment site except no soil was replaced (Figure 2). The soil of the control site was clay loam (porosity: 0.46 $m^3 m^{-3}$, saturated hydraulic conductivity: 2.14 cm day^{-1}) (Wang *et al.* 1996, Bird *et al.* 2000). The finished landscape of both control and treatment sites followed the UCD parking lot standard. Mulch (i.e. wood chips from 5.1 cm to 7.6 cm deep) was uniformly spread over the entire planting strip. Figure 3 shows the landscape before, during, and after the system installation. This bioswale was designed to eliminate runoff from a 10-year storm event (7.9 cm rainfall) or 97% of all annual rainfall events (based on rainfall analysis of Davis' 2000 precipitation data), as per local development requirements (Karoly 1991).

After installation the system was tested with potable water sprayed from a water truck to simulate stormwater runoff. The bioswale stored and infiltrated more than 15.1 m^3 of water, equivalent to 7.2 cm precipitation and nearly a 10-year storm. There was no settling of soil in the bioswale.

Runoff measurement system

Because of the relatively flat landscape between the parking lot and the street, surface runoff measurements were conducted through a surface-subsurface water collection and measurement system. Surface runoff was directed to flow off each test area by the elevated redwood board and into a 5.1 cm PVC pipe. One end of this PVC pipe was located at the lowest corner of the test area (i.e. the outlet point) at ground surface level and the other end was connected to a 189.0 litre underground water storage tank located nearby

(Figure 4). A submergible utility waste water pump (EF33, Grundfos Pumps Corporation) was located inside the water storage tank to pump runoff from the tank to street. The water level in the storage tank was controlled by a float switch. The pump's working status was monitored by a current transformer (CS10-L, Campbell Scientific, Inc.) and automatically recorded by a data logger (CR10, Campbell Scientific, Inc.). A flow-proportional drainage water sampling method (de Vos 2001) was used to collect water samples for water quality analysis. A flow controller was installed in the pump's outlet pipe to divide the outflow from the pump to the street and to a 19.0)litre water sample container. The flow ratio between the runoff to street and runoff to the water sample container was set at 600:1 so that sufficient water was sampled from small storm events (3.3 mm rainfall) and the container did not overflow during large storm events (10 years storm, 7.9 cm rainfall).

On-site precipitation data was obtained from a nearby CIMIS (California Irrigation Management Information System) station. This CIMIS station was located 1500.0 m west of the study site. The precipitation measured at this CIMIS station represented the precipitation at the study site because of the relatively flat topography.

Measurement system calibration

The runoff measurement system was calibrated to obtain the pumps' actual performance data. One data feature is the relationship between the pump's operation time and the amount of water pumped from the system. Potable water was brought to the site in a 1135.5)litre water tank and a precision water meter (GPI TM100N, Great Plains Industries, Inc) was used to measure the amount of water added to the runoff storage tank. The pumps' on-off time was recorded by the data-logger.

Water quality analysis

Storm runoff quality analyses focused on standard pollutant parameters (Myers *et al.* 1982, USEPA 1983a). The measured chemical constituents included minerals (i.e. Total Kjehldahl Nitrogen (TKN), ammonia (NH_4), nitrate (NO_3), and Phosphorus (P)), metals (zinc (Zn), copper (Cu), iron (Fe), chromium (Cr), lead (Pb), nickel (Ni), mercury (Hg), and cadmium (Cd)), Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC)), and Total Petroleum Hydrocarbons (TPH) (i.e. gas, diesel, and motor oil). The quality analyses also contained conventional

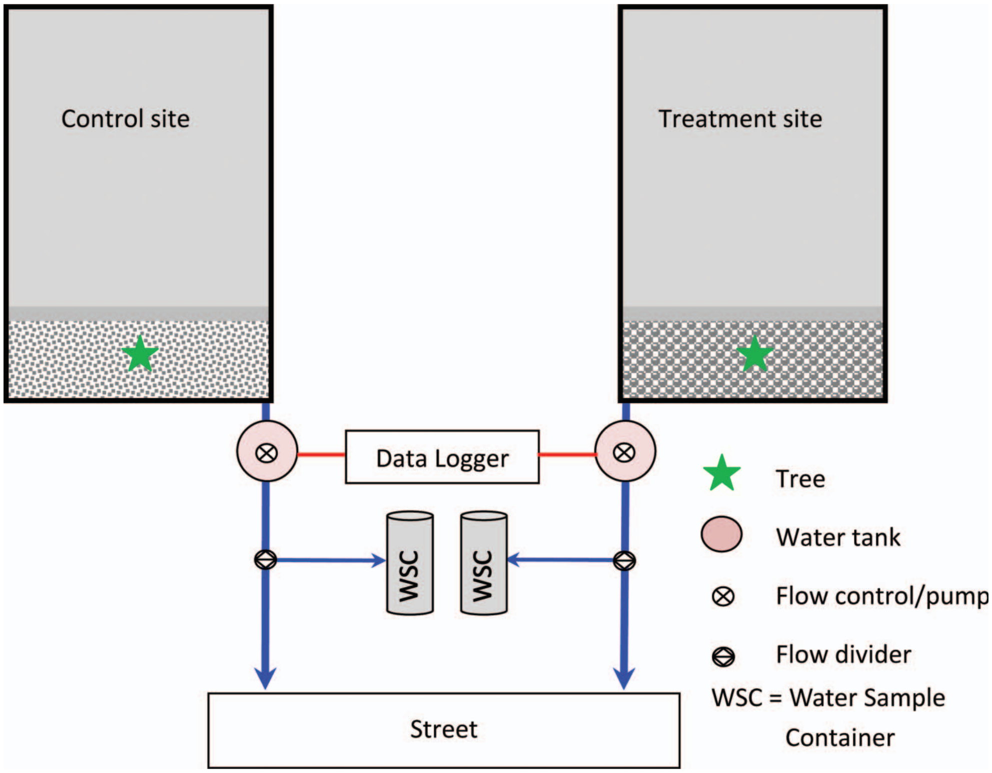

Figure 4. Measurement and water sample collection system. For each site, surface runoff flows to underground water storage tank. The flow controller inside the tank controls water level. Water leaves the tank via a water pump. The water from the pump passes through a flow divider which divides water flows to water sample container and flows to street.

physical properties such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Total Suspended Solids (TSS), because they are of primary concern in runoff water quality. Total dissolved solids (TDS) are differentiated from total suspended solids (TSS), in that the latter cannot pass through a sieve of two micrometers and yet are indefinitely suspended in solution.

The majority of these water quality parameters were analysed at the Division of Agriculture and Natural Resources (ANR) Analytical Laboratory, University of California. The ANR Analytical Laboratory performs water quality analyses for these selected chemical constituents with USEPA recommended or standard analytical methods. The Method Detection Limit (MDL) for minerals was 0.05 mg/L except TKN, for which the MDL was 0.10 mg/L. For metals, the MDL was 0.1 mg/L for copper, 0.02 mg/L for zinc, and 0.05 mg/L for both nickel and lead. For chromium and cadmium, the MDL was 0.005 mg/L, and selenium and mercury had an MDL of 1.0)μ g/L. The organic carbon and hydrocarbon analyses were conducted by California Laboratory Services (CLS Labs). CLS is an USEPA certified full service environmental chemistry laboratory. MDL were 1.0 mg/L for TOC and DOC and 0.05 mg/L for TPH.

The nature of the pollutant concentrations measured for each storm event represented the Event Mean Concentration (EMC) because the water samples were flow-proportional (USEPA, 2002). Standard statistical analytical methods (i.e., mean, minimum, maximum concentrations, standard deviation, and t-test) were used to perform water quality statistical data analysis.

Results and discussion

Storm runoff measurements were conducted from February 2007 through October 2008. There were 50 storm events with a total precipitation of 563.8 mm during this time period (Table 1). Storm events were separated based on a 24-hour rainless period (Xiao *et al.* 2000b). Storm size ranged from 0.1 mm to 88.9 mm. Rainfall averaged 11.28 mm per storm. Most storms were small, with 70% of the storm events less than 6.4 mm. In contrast, six storms accounted for more than half (53%) of the total precipitation.

Storm runoff reduction

Of the 50 total storm events, only 20 storms generated surface runoff from the control site and 11 storms generated runoff from the treatment site. Runoff coefficients, ratio of runoff to precipitation, for these storms ranged from 0–76% for the control site and from 0–6% for the treatment site. Runoff from the control site accounted for 50% of total precipitation

Table 1. Storm events of the study period.

		Precipitation*				Precipitation	
Event number	Date	mm	in	Event number	Date	mm	in
1	2/8/07	50.20	1.98	26	11/11/07	20.00	0.79
2	2/13/07	3.90	0.15	27	11/18/07	0.30	0.01
3	2/23/07	5.20	0.20	28	11/20/07	0.10	0.00
4	2/25/07	22.90	0.90	29	12/5/07	3.40	0.13
5	3/9/07	0.10	0.00	30	12/7/07	39.80	1.57
6	3/21/07	2.10	0.08	31	12/17/07	24.70	0.97
7	3/23/07	0.10	0.00	32	12/28/07	5.30	0.21
8	3/27/07	1.00	0.04	33	1/4/08	66.10	2.60
9	4/11/07	5.00	0.20	34	1/22/08	88.90	3.50
10	4/18/07	0.10	0.00	35	1/28/08	5.08	0.20
11	4/22/07	11.80	0.46	36	1/30/08	3.90	0.15
12	5/3/07	3.30	0.13	37	2/1/08	10.10	0.40
13	5/4/07	2.90	0.11	38	2/3/08	10.50	0.41
14	5/12/07	3.20	0.13	39	2/9/08	0.10	0.00
15	6/5/07	0.10	0.00	40	2/12/08	0.10	0.00
16	6/12/07	0.10	0.00	41	2/14/08	0.10	0.00
17	9/23/07	0.10	0.00	42	2/20/08	8.00	0.31
18	10/2/07	0.50	0.02	43	2/22/08	38.80	1.53
19	10/6/07	0.20	0.01	44	2/27/08	0.10	0.00
20	10/10/07	19.10	0.75	45	3/28/08	0.80	0.03
21	10/12/07	0.10	0.00	46	3/29/08	0.30	0.01
22	10/13/07	9.00	0.35	47	4/22/08	31.50	1.24
23	10/17/07	3.20	0.13	48	10/4/08	2.00	0.08
24	10/30/07	0.30	0.01	49	10/31/08	54.10	2.13
25	11/2/07	0.10	0.00	50	11/4/08	5.10	0.20

*Precipitation was measured at 100th of inches.

during this measurement period. In contrast, only 3% of rainfall falling on the treatment site contributed to surface runoff flowing off the site (Table 2). No runoff flowed to the street from either site when precipitation was less than 3.3 mm or 50% of the storm events. From the treatment site, there was no runoff flow to street for all storms less than 9.0 mm or 70% of the total storm events. Storm runoff in the treatment site was significantly reduced. The runoff from the treatment site was 94% less than runoff from the control site. The rate of runoff reduction of this system was similar to other biofilter studies. For example, a field test of biofilters in Australia found that they reduced peak runoff flow rats by at least 80% (Hatt *et al.* 2009).

Initially, the bioswale was designed to be 1.2 m deep to retain and treat storm runoff from a 10-year event. However, the bioswale's depth was reduced by 0.3 m during field installation to avoid damaging underground utility and communication cables. The resulting 25% volume reduction may explain why runoff was observed for storm events with less than a 10-year return frequency.

Pollutant reduction

There were 21 chemical constituents analysed in this project (Table 3). All detectable water quality constituents' concentrations from the control site were

Table 2. Runoff and runoff coefficient by storm event.

Event Number	Precipitation (mm)	Control site			Treatment site		
		Litre	Gallon	RC[**]	Litre	Gallon	RC
1	50.2	4,425.4	1,169.1	0.41			
2	3.9	126.7	33.5	0.15			
3	5.2	271.5	71.7	0.25			
4	22.9	2,027.2	535.5	0.42			
12	3.3	208.2	55.0	0.30			
20	19.1	2,140.4	565.4	0.53	178.7	47.2	0.04
22	9.0	1,049.8	277.3	0.55	89.4	23.6	0.05
26	20.0	1,601.6	423.1	0.38	175.7	46.4	0.04
30	39.8	5,211.2	1,376.6	0.62	364.0	96.2	0.04
31	24.7	2,216.6	585.6	0.42	89.0	23.5	0.02
33	66.1	10,653.8	2,814.4	0.76	654.9	173.0	0.05
34	88.9	14,103.8	3,725.8	0.75	1,128.1	298.0	0.06
35	5.1	330.3	87.2	0.31			
36	3.9	250.5	66.2	0.30			
37	10.1	1,465.0	387.0	0.68	93.5	24.7	0.04
38	10.5	1,575.1	416.1	0.71	94.1	24.9	0.04
42	8.0	766.6	202.5	0.45			
43	38.8	4,706.4	1,243.3	0.57	273.0	72.1	0.03
49	54.1	5,666.5	1,496.9	0.49	633.0	167.2	0.06
50	5.1	576.9	152.4	0.53			

*Only storms that had runoff flow off the system are listed in this table. The gray areas are storms with no runoff flow out the system. The date of each storm event was listed in Table 1.

[**] RC: Runoff coefficient.

Table 3. Summary of runoff quality measurement.

Constituent	Control site		Treatment site	
	EMC range	Median EMC	EMC range	Median EMC
DOC (mg/L)	10.00–76.00	17.50	7.50–73.00	14.50
EC (dS/m)	0.04–1.00	0.15	0.05–0.29	0.08
Fe (mg/L)	0.40–2.35	0.63	0.85–3.40	2.15
NH4-N (mg/L)	0.03–1.03	0.09	0.03–0.64	0.07
NO3-N (mg/L)	0.07–5.87	0.40	0.03–13.23	0.25
P (mg/L)	0.10–2.50	0.40	0.20–1.90	0.30
pH	6.70–7.70	7.41	7.00–7.80	7.45
PO4-P (mg/L)	0.08–2.20	0.29	0.07–1.53	0.20
TDS (mg/L)	80.00–305.00	95.00	35.00–260.00	85.00
TKN (mg/L)	0.55–8.10	1.48	0.95–8.20	1.35
TOC (mg/L)	11.00–35.00	22.00	7.80–25.00	20.00
TSS (mg/L)	6.00–23.00	12.50	9.00–28.50	17.79

Table 4. Pollutant loading by storm events.

Event Number	Control site											Treatment site										
	PT**	PS***	TKN	NO_3	NH_4	Fe	Zn	TOC	DOC	TDS	TSS	PT	PS	TKN	NO_3	NH_4	Fe	Zn	TOC	DOC	TDS	TSS
1	11.1	9.7	35.8	26.0	4.6	2.4	0.9	154.9	336.3	1,261.1	112.8											
2	0.3	0.3	1.0	0.7	0.1	0.1	0.0	4.4	9.6	36.1	3.2											
3	0.7	0.6	2.2	1.6	0.3	0.1	0.1	9.5	20.6	77.4	6.9											
4	5.1	4.4	16.4	11.9	2.1	1.1	0.4	70.9	154.0	577.7	51.7											
12	0.5	0.5	1.7	1.2	0.2	0.1	0.0	7.3	15.8	59.3	5.3											
20	5.4	4.7	17.3	12.6	2.2	1.2	0.4	74.9	162.7	609.9	54.6	0.3	0.3	1.5	0.6	0.1	0.2	0.0	3.8	13.0	39.3	3.5
22	2.2	2.0	4.6	13.9	0.1	0.4	0.1	36.7	56.7	320.1	12.6	0.0	0.0	0.1	0.5	0.0	0.2	0.0	1.9	1.7	23.2	0.5
26	3.3	3.1	7.0	21.2	0.1	0.6	0.1	56.1	86.5	488.5	19.2	0.0	0.0	0.3	0.9	0.0	0.4	0.0	3.7	3.3	45.7	1.1
30	2.6	1.6	7.3	2.5	0.8	2.6	0.3	57.3	125.1	469.0	52.1	0.2	0.1	0.9	0.1	0.0	0.7	0.0	4.4	6.2	29.1	10.2
31	0.9	0.6	3.4	0.7	0.1	1.2	0.4	53.2	22.2	199.5	42.1	0.0	0.0	0.1	0.0	0.0	0.3	0.0	2.2	0.7	6.2	0.8
33	2.1	1.8	12.3	1.8	1.2	25.0	0.5	213.1	106.5	852.2	245.0	0.1	0.1	0.6	0.0	0.0	1.4	0.0	12.4	4.9	52.4	5.9
34	1.4	1.1	7.8	1.0	0.4	9.9	0.7	169.2	141.0	1,198.7	401.9	0.3	0.2	1.1	0.1	0.0	3.8	0.1	8.8	8.5	39.5	11.3
35	0.0	0.0	0.2	0.0	0.0	0.2	0.0	4.0	3.3	28.1	9.4											
36	0.1	0.0	0.2	0.0	0.0	0.4	0.0	2.8	2.8	25.0	2.9											
37	0.3	0.2	1.2	0.2	0.0	2.1	0.1	16.1	16.1	146.5	16.8	0.0	0.0	0.1	0.0	0.0	0.2	0.0	1.1	1.1	4.7	1.6
38	0.6	0.5	3.2	1.3	0.2	1.7	0.1	55.1	50.4	189.0	26.1	0.1	0.0	0.2	0.2	0.0	0.2	0.0	2.0	1.8	8.9	1.4
42	0.3	0.2	1.6	0.6	0.1	0.8	0.0	26.8	24.5	92.0	12.7											
43	1.9	1.4	9.6	3.9	0.7	5.2	0.2	164.7	150.6	564.7	78.1	0.2	0.1	0.6	0.5	0.0	0.4	0.0	5.7	5.2	25.9	4.1
49	14.2	12.4	45.9	33.2	5.8	3.1	1.1	198.3	430.6	1,614.8	144.5	1.2	1.0	5.2	2.1	0.4	0.5	0.0	13.3	46.2	139.2	12.3
50	1.4	1.3	4.7	3.4	0.6	0.3	0.1	20.2	43.8	164.4	14.7											
Total	54.3	46.5	183.5	137.8	19.7	58.7	5.6	1,395.5	1,959.1	8,973.9	1,312.7	2.6	1.9	10.6	5.1	0.7	8.3	0.3	59.3	92.6	414.2	52.7

*Only storms that had runoff flow off the system are listed in this table. The gray areas are storms with no runoff flow off the system.

**PT: Total phosphorus.

**PS: Dissolved phosphorus.

consistently higher than those measured from the treatment site except for iron and pH. The iron and pH were consistently lower from the control site than those measured from the treatment site. However, there was no statistically significant difference between the runoff's pollutant concentrations between the two sites. Only Zn and Fe were detected from both treatment and control sites. The other metal elements (i.e. Cu, Cd, Cr, Pb, Ni, and Hg) were below the laboratory's Method Detection Limit (MDL). This may be due to relatively clean runoff from this lot (Xiao *et al.* 2006) as compared with runoff data from USEPA (USEPA 1983b). Diesel and motor oil were not detected from runoff samples collected from both sites. This may be due to filtering by the mulch applied on top of the planting strip. Hong *et al.* found that a thin layer of mulch on the surface of a bio-retention facility can effectively reduce oil and grease from urban stormwater runoff (Hong *et al.* 2006).

Loading reduction

The bioswale not only reduced the amount of runoff but also reduced runoff pollutant loading. Thus, pollutant loading that contributed to downstream runoff was different for the two sites. Table 4 lists pollutant loading from each storm event. This bioswale system reduced minerals by 95.3%, metals by 86.7%, organic carbon by 95.5%, and solids by 95.5%. The average loading reduction of this bioswale was 95.4%. A similar pollutant reduction rate was found in large-scale biofilter column test, where up to 70% N and 85% P were reduced (Bratieres *et al.* 2008). Blecken *et al.* found that biofilters can remove 90% of metals from stormwater (Blecken *et al.* 2009). Total loading from the control and from the treatment sites were 14,147.3 g and 675.1 g, respectively. Solids (i.e. TDS and TSS) accounted for the majority of the loading (more than 72%), followed by organic carbon (i.e. TOC and DOC) which accounted for more than 23% of the total loading. Minerals (i.e. nitrogen (TKN, ammonia, and ammonium) and phosphorus (total and dissolved)) accounted for 3% of the total loading. The total amount of metals (i.e. Zn and Fe) from the treatment site was much smaller than from the control site (8.6 g vs. 64.3 g). However, 1.3% of loading from the treatment site were metals compared to 0.5% metals from the control site. The lava rock could be a source of iron, accounting for the higher iron concentration found in water samples collected from the treatment site. TPH from both sites were below the laboratory detectable limit.

The pH measured in the water samples was consistently higher for the treatment site than the control site. At a confidence level of 0.05, there was no significant difference in pH measured in the runoff samples from the two sites. However, the pH value was 4% higher in the runoff from the treatment site (average pH) =)7.53) than from the control site (average pH) =)7.25). Relatively higher alkalinity for engineered soils was observed (Day and Dickinson 2008), and is very likely caused by the lava rock. Higher soil pH should be considered when selecting trees for the engineered soil because some species are less tolerant than others.

Water samples collected in this study were storm event based or water quality represented by EMC. Without taking into account the dynamics of the process, there was uncertainty in measured water quality data. Further water quality data collection from this study site would allow long-term performance analysis and reduce the uncertainty (Harmel and King 2005, Gulliver *et al.* 2010).

Tree growth

During this 16-month study, the tree growth at the treatment site was slightly better (visual observation of leaves and new branches) than growth at the control site. The engineered soil provided better aeration and drainage for the trees during the winter, when rainfall was abundant. However, during the dry summer the tree planted in the bioswale required more frequent irrigation due to drainage characteristics of the engineered soil. More frequent irrigation, especially while tree roots are getting established, may increase the cost of irrigation. Although not observed in this study, trees planted in the engineered soil may require supplemental fertilisation because of the limited amount of soil in the mix.

Bioswale vegetation has proven to play an important role in the process of removing pollutants from runoff (Barrett *et al.* 1998, Mazer *et al.* 2001, Wong *et al.* 2006). The trees in this study were too young and small to achieve a high level of performance. Longer-term studies are required to provide more information about the changing dynamics of tree interception and evapotranspiration on runoff reduction and to provide information about the physical and chemical properties of the engineered soil change over time that may affect the performance of the system.

Conclusion

Field experiment results indicate that the bioswale effectively reduced the amount of storm runoff and pollutant (i.e. minerals, metals, organic carbons, hydrocarbons, and solids) loading from the parking lot. The bioswale reduced runoff by 88.8% and the total loading by 95.4%. Individual water quality constituent reduction rates ranged from 86% for iron to 97% for nitrogen. Pollutant removal rates for minerals, metals, organic carbon, and solids were 95%, 87%, 95%, and 95%, respectively. The high porosity of the engineered soil provided more space to store runoff and better aeration to the tree root system with the compacted clay loam soil at the control site.

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