Bojana Anglin
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Soil for Rain Gardens in Mediteranean-climate Regions

Abstract

Urbanization increases stormwater run-off volumes through the widespread use of impervious surfaces. This leads to localized flooding, water pollution and morphologically degraded water bodies. Rain gardens – a shallow, vegetated form of bioretention – are one strategy for mitigating these hydrologic consequences of urbanization. Rain gardens in highly urban areas typically require greater infiltration rates due to their smaller volumes. The application of urban rain gardens in a Mediterranean climate is further challenged by contrasting wet and dry seasons. These have significant implications for run-off, infiltration, treatment and plant survival. Soil selection is critical to all of these, because it performs the necessary and competing functions of drainage and plant-available water retention. An appropriate soil mix will sufficiently infiltrate stormwater to reduce run-off, while also holding some plant-available water to reduce irrigation needs during dry periods. Similarly, an appropriate plant palette will utilize species adapted to drought, well-drained soils and periodic flooding. The San Francisco Bay Area has a number of rain garden soil specifications, with little data on relative performance and minimal monitoring of existing sites. In this research, I will examine current soil specifications by regional agencies and municipalities. Furthermore, I will measure infiltration rates at nine locally sampled rain gardens sites, comparing these to cultivation needs of associated plant species. The implications for other Mediterranean climate regions, particularly southern Europe, are significant. While the Water Framework Directive recommends that stormwater be dealt with at the source, the EU and particularly the Mediterranean member states lag in rain garden implementation. A better understanding of the soil requirements for Mediterranean-climate rain gardens will advance their implementation in California and Mediterranean-climate regions generally.

Problem statement

Background

Urbanization increases stormwater run-off volumes through the widespread use of impervious surfaces. This leads to localized flooding, water pollution and morphologically degraded water bodies. A number of mitigation strategies exist, encapsulated under the umbrella terms Best Management Practices or Low Impact Development. Bioretention is a broad term used to describe any technique that maximizes collection and filtration of stormwater run-off (Tom Richman & Associates, 1997). Rain gardens are a shallow, vegetated type of bioretention that utilize a flow-based treatment control design (EOA, Inc. 2005; San Bernardino Co, 2005). Rain gardens range both in size and form, from small planter boxes to larger, unconfined swales and basins. Functionally, rain gardens filter pollutants from stormwater, prevent flooding by detaining and infiltrating run-off, and reduce peak-flows in urbanized creek channels. Urban rain gardens tend to be small because of higher spatial densities in cities, as well as to minimize the burden on developers (Stromberg, pers. com., 2009). Thus, they are under greater pressure to drain quickly, particularly if their impervious surface tributary is large. These higher infiltration rates can be problematic for plant cultivation. Furthermore, rain garden implementation in a Mediterranean climate is challenging because contrasting wet and dry seasons have significant implications for run-off, infiltration, treatment and plant survival.

Soil selection is the primary determinant of rain garden performance, particularly under Mediterranean climate and urban constraints. An appropriate rain garden soil mix will sufficiently infiltrate and drain stormwater during the wet season, while also holding enough plant-available water to reduce irrigation during dry periods. The ability of rain garden plants to thrive under a Mediterranean climate, with minimal irrigation, depends on the soil's ability to perform the necessary and competing functions of drainage and water storage. These soil functions specifically result from soil texture (relative proportions of sand, silt and clay) and soil porosity.

Plant species selection, a secondary determinant of rain garden performance, is important to any discussion of soils. Plant species minimally affect some soil properties and functions, including compaction through progressive pore clogging (Pitt et al., 2007) and pollutant removal (Aldrete and Scharff, 2005). More importantly, plants are the most visible piece of a rain garden, thus successful establishment is critical. Because different plant species have varying tolerances for both soil inundation and drought, rain garden designers must match these qualities to rain garden soil infiltration rates for maximum compatibility. Because of the subordinated relationship between soils and plant species, my research focuses first on rain garden soils, particularly infiltrations rates and then on the growing needs of plant species associated with each rain garden**.** I assess the compatibility of soil and plant characteristics as indicators of overall rain garden effectiveness, both functionally and aesthetically.

Rain garden soil specifications: the need for Bay Area research

Many rain garden soil specifications are broad guidelines for all temperate climates, and ignore the contrasting wet and dry seasons that specifically define Mediterranean climates. For example, the Facility for Advancing Water Biofiltration, a leading international authority, has very detailed infiltration rate guidelines, but these are developed for temperate climates as a whole (FAWB, 2008). As a result, San Francisco Bay Area guidelines often derive from more established traditions of rain garden implementation in humid regions such as Maryland and the Pacific Northwest (Stromberg, pers. com., 2009). Nevertheless, the successful transferability of soil specifications between humid and Mediterranean climates is questionable (Herrera, pers. com., 2009).

Currently, three Bay Area counties have rain garden soil specifications: Contra Costa, Alameda and Sonoma Counties. The specifications vary between them. Furthermore, the soil mix recommendations are often ambiguous, deferring to the contractor or landscape architect. This flexible approach intends for local conditions to dictate final soil mixes, however, it requires follow-up monitoring, which is currently not common practice (Nguyen, pers. com., 2009). My research addresses this need.

Furthermore, the San Francisco PUC, a proponent of rain garden implementation, is actively seeking more precise information on rain garden soil mixes appropriate to the Bay Area (Diamond, pers. com., 2009; Jencks, pers. com., 2009). This research project will address some of the PUC's questions. I do this first through examination of current specifications by different regional agencies and municipalities. I then determine infiltration rates at nine established Bay Area rain gardens. I assess whether these meet standards specified by regional municipalities. Furthermore, I assess the drought-tolerance of plant species at each site. Finally, I compare infiltration rate, with drought-tolerance and drainage requirements of associated plant species to determine the relative compatibility between soil and plant selection for each site.

Methods

Identifying existing regional rain garden soil specifications and sites

Through literature review, phone and email interviews, I compiled a spreadsheet of rain garden soil specifications relevant to the San Francisco Bay Area (table 1). I used the same methods to identify nine Bay Area rain garden sites and locations.

Site visits and infiltrometer tests

I visited nine rain garden sites on April 25th and 26th (table 2; appendices 2 - 4). I conducted an *in situ* infiltrometer test, with two replicates, at each site. I used a single-ring infiltrometer under falling head (figure 1) to measure infiltration rate *in situ*. I adapted a single-sheet galvanized metal master duct (8" height; 7" diameter) to function as an infiltrometer. At each site, I scraped away the top layer of mulch to expose the soil beneath. The sharp edges of the duct facilitated burial of the infiltrometer bottom 1" below the soil surface. I then added 1L of water into the infiltrometer cavity. I held a ruler to the inside wall of the infiltrometer, with the bottom of the ruler flush to the soil surface. Using a stopwatch, I recorded the time associated with incremental ¼" drops in water height, until all of the water had infiltrated into the rain garden soil. I then converted the total infiltration time into hours and divided this number into the total water column height of 1L (1.25"), to determine the infiltration rate in inches per hour.

Because I developed my method for measuring infiltration independently, it was necessary to calibrated my measurements so that they could be compared to standard infiltration rates. To do this, I used the same infiltration measuring method, over three replicates, on a sand medium of known particle size: Cemex's Lapis Lustre Dried Sand, grade #2-/16. Using, a 5-gallon bucket filled to capacity with the sand medium, I performed the measurements in the Berkeley Environmental Fluids Laboratory, at UC Berkeley. I then calculated infiltration using Hazen's equation:

$k = 100\ D_{10}^{2}$, where k = infiltration rate; D_{10} = the particle size at the 10th percentile of the medium's particle size range, starting from the lower values.

To determine D_{10} , I contacted the sand provider for specifications on particle size of this sand grade. I plotted the range of particle sizes in Excel and used the best-fit curve function to determine a particle size value for D_{10}.

By dividing the infiltration rate results from my field infiltrometer method with results obtained from Hazen's equation, I derived a coefficient that I used to multiply my field results to yield corrected infiltration rates that can be compared to infiltration rate specifications in standard stormwater guidelines. The calculations are seen in Appendix 1.

Plant Species: Drought-tolerance and drainage requirements

During my site visits, I recorded the plant species growing in each rain garden. I then assigned to each species drought-tolerance values, along with drainage requirement values. Using species' water-needs information provided by EBMUD's publication, *Plants and Landscapes for Summer-dry Climates* (2004) and the *Sunset Western Garden Book* (2001), I assigned to each species a rating from 1-5, with higher numbers corresponding to higher levels of drought-tolerance and drainage requirements. I used these individual species ratings to calculated average ratings for each rain garden site based on species occurrence.

Results

Soil specifications

Rain garden soil specifications vary by the issuing agency or authority, with some overlap (table 1). The Facility for Advancing Water Biofiltration (FAWB), a recognized Australian leader in rain garden design, specifies optimal infiltration rates for temperate climates: 4 to12 in/hr. The FAWB further specifies a maximum recommended infiltration rate of 24 in/hr. All local authorities, including Alameda, Contra Costa and Sonoma Counties, agree on a 5 in/hr minimum infiltration rate. In addition, some counties and cities have established strict maximum infiltrations rates of 50 in/hr, including Contra Costa County and the city of Emeryville (Schultze-Allen, 2009). Soil media recommendations throughout the municipalities generally have wide parameters for acceptable particle sizes and components. Sonoma County has the most general guidelines and only specifies a loamy sand. Alameda County differs slightly by specifying a sandy loam. It also recommends the following general percent compositions: 10% topsoil; 85% construction sand, without particle size specifications; and 5% compost. Contra Costa County gets more specific. It has two soil mixes, each with a different relative proportion of fine sand. Mix A has 50-60% fine sand; Mix B has 60-70% fine sand. In both mixes, the remaining components are topsoil and compost. The FAWB has the most defined soil component parameters, with recommended relative proportions for each particle size class. The FAWB, however, has no mention of compost in its specifications.

Infiltration rates

Infiltration readings using the field infiltrometer method under falling head correlated fairly well with infiltration rate calculated using Hazen's equation. The standardization coefficient (field method:calculation method) was 0.83 (Appendix 1).

Corrected rain garden infiltration times varied greatly between sample sites (table 4; figure 2). Emeryville Station East had the highest infiltration rate, 45.1in/hr. Mint Plaza and the Shannon Center also exhibited fairly high infiltration rates: 36.6 and 33.3 in/hr, respectively. Google Day Care and the Dublin Senior Center both scored in the middle-range: 21.9 and 23.9 in/hr, respectively. West Elm and Shotwell Greenway both fell at the low-end of the spectrum: 6.1 and 5.0 in/hr respectively. Muir Labs exhibited the lowest infiltration rate, 3.6 in/hr.

Plant species and drought-tolerance

The plant palette at each site ranged from a single species to more than a dozen (table 5).

The Glaushaus rain garden included a single species of *Juncus*. The Shotwell Greenway rain garden included thirteen plant species. Average drought-tolerance ratings of each rain garden site varied, depending on the drought-tolerance of associated plant species (Table 6; figure 3). West Elm had the highest range of drought-tolerances represented in its plant palette; values ranged from 1 to 4. Glashaus and Muir Labs had the least amount of drought-tolerance variation represented by plant species; drought-tolerance values at both sites remained constant across plant species that occurred there. The Shotwell Greenway and Google Day Care had the highest average levels of drought tolerance: respectively, 3.9 and 3.6 out of 5 possible points. Glashaus, with a rating of 1, exhibited the lowest drought-tolerance of all the sites.

Plant species and drainage- requirements

Some of the sites surveyed also demonstrated very broad ranges for drainage requirements by associated plant species. Plant species growing in each of the West Elm, Shotwell Greenway and Google Day Care all exhibited a wide range of drainage requirements. By contrast, plant species occurring at each of the Emeryville Station East, Glashaus, Muir Labs and Shannon Center sites had the same requirements: these sites had no range of drainage requirement values. Of these, Emeryville Station East and Glashaus were single species sites.The Emeryville Station East site had the highest total average drainage requirement rating: 5 out of 5. Mint Plaza followed with 4.5 out of 5 points. Glashaus had the lowest total average drainage requirement of 1.

Discussion

My method for testing infiltration rates didn't conform to standard protocol, such as that specified by the ASTM. For this reason, I attempted to calibrate my results by using the same field method on a sand of known particle size, with a calculable infiltration rate based on

Hazen's equation. I used these results to determine a conversion coefficient that I used to correct my field results so that they could be compared to infiltration rates specifications (Appendix 1). Nevertheless, Hazen's equation is a simplified method for determining infiltration rate based on particle size only. The equation works best for sand media and ignores compaction and particle grain shape (Schafmeister, 2007). Therefore, any comparisons that I make between my field results and infiltration rate specifications should be considered approximations. The high infiltration rates that I measured at some sites, however, were, to some degree, validated by Peter Schultz Allen, environmental analyst for the city of Emeryville. He informed me that Filterra units, a type of prefabricated rain garden used locally and nationally, are designed to have a 100in/hr infiltration rate. Recently, the city of Emeryville and Contra Costa county updated their own specifications to limit infiltration rate to 50 in/hr, in response to the implementation of designs such as Filterra's. Thus, it's quite conceivable that Emeryville Station East, for example, does indeed have the high infiltration rate of 45 in/hr that I measured.

The FAWB guidelines state that higher infiltration rates increase the need for irrigation by rain garden plants. Infiltration rates above 24 in/hr pose problems for plant growth due to poor water retention by soils and may also result in leaching of pollutants. Lower infiltration rates, however, require a larger rain garden area to meet drainage needs. Drainage rates below 4 in/hr pose problems for plant growth due to insufficient aeration of roots (FAWB, 2008). Regional SF Bay area specifications all agree on a minimum infiltration rate, 5 in/hr, comparable to the FAWB. Two of the three regional counties with developed guidelines also specify a maximum infiltration rate of 10 in/hr, also comparable to the FAWB's optimal maximum of 12 in/hr. Contra Costa County and the city of Emeryville have significantly higher maximum limits of 50 in/hr. This discrepancy begins to hint at the level of uncertainty regarding appropriate levels of rain garden infiltration, particularly in the context of urban and Mediterranean constraints.

Only two of the sites surveyed met the FAWB criteria for optimal infiltration rates: 4 – 12 in/hr. These sites were Shotwell Greenway (5.0 in/hr) and West Elm (6.2 in/hr). These also met Alameda and Contra Costa Counties' guidelines of 5 – 10 in/hr infiltration rates. Interestingly, Shotwell Greenway simply daylighted the native soil beneath stretches of pavement and added minimal amendment to achieve this exemplary infiltration performance (Plant SF, 2009).

Not all sampled sites met minimum infiltration specifications, even when soil was relocated. The above-grade flow-through planters at Muir Labs, with an infiltration rate of 3.6 in/hr, fell short of both local and FAWB minimum infiltration rates guidelines. The planters are raised 2.5' above grade: clearly, soil had been intentionally moved to manage roof run-off at its current location, however, there was little forethought regarding its role in the performance of the rain garden. Additionally, 33% of the sites surveyed had infiltration rates greater than 24 in/hr, a threshold beyond which run-off pollutants may leach from the soil and plant survival becomes an issue due to less available soil water (FAWB, 2008). These sites were Emeryville Station East, Mint Plaza, and the Shannon Center. All three sites drain run-off from non-polluted sources such as roofs or plazas, therefore groundwater contamination isn't an issue. Nevertheless, higher plant irrigation needs during the dry season are a potential issue depending on plant species selected for the site. Of these three sites, Mint Plaza had the most drought-tolerant plant palette and likely required the least amount of irrigation during the dry season. The remaining 22% of sites had infiltration rates greater than FAWB recommendations, but below the critical threshold of 24 in/hr. Plants occurring at these sites would typically require more irrigation during dry periods to compensate for increased drainage from soil media.

Appropriate choice of plant palette can mitigate increased irrigation needs associated with high drainage. For example, Emeryville Station East exhibited the highest infiltration (45 in/hr), and used a single, drought-tolerant plant species with high drainage requirements (*Chondropetalum tectorum*). Drought-tolerance for the site was 3 out of 5 possible points, indicating low-to-moderate water needs; drainage requirements for the site were even higher: 5 out of 5 possible points. This choice of plant species reflects an attempt by the rain garden designer to match soil characteristics to plant growing needs.

Sites characterized by a mismatch between rain garden soil and plant species will need extra irrigation or will experience plant die-off. An example of the latter is likely at the West Elm and Shotwell Greenway sites. These both both exhibited very low drainage (6.2 and 5.0 in/hr, respectively), yet the species occurring at both sites scored high in terms of drought-tolerance and drainage requirements. Such sites may exhibit plant mortality over time. In fact, the Shotwell Greenway site contained several dead plants (Appendix 4), possibly the result of incompatible soil characteristics and plant growing needs.

The broad range of plant species' drought- and drainage tolerances at some sites, such as West Elm, raise further issues regarding the long-term viability of the rain garden and its associated plant species. Of all the sites surveyed, species at West Elm exhibited the highest range of both drought-tolerances and drainage requirements. Pairing drought-tolerant species with water-loving species in a single site creates an inevitable mismatch between some species and the amount of available water in the soil. West Elm is a new project (finished in February, 2009) and the full impact of the soil conditions on plant species viability has not yet been seen.

Over time, the plant palette here will inevitably become narrower as those species with higher drought-tolerances and drainage needs die off due to the low infiltration rate of the soil.

Conclusion

Rain gardens are a promising strategy for mitigating increased urban run-off. Rain gardens in highly urban areas typically require greater infiltration rates due to both their smaller volumes and greater stormwater run-off from surrounding impervious surfaces. Infiltration rates above 24 in/hr, however, must be regulated due to the threat of groundwater contamination. Furthermore, if a high infiltration rate is implemented, the plant palette must coincide, for the project to be successful both aesthetically and functionally. The application of urban rain gardens in a Mediterranean climate is further challenged by contrasting wet and dry seasons. These have significant implications for run-off, infiltration, treatment and plant survival. Soil selection is critical to all of these, because it performs the necessary and competing functions of drainage and plant-available water retention. An appropriate soil mix will sufficiently infiltrate stormwater to reduce run-off and aerate plant roots. It will also hold some plant-available water to reduce irrigation needs during dry periods. Similarly, an appropriate plant palette will utilize species adapted to drought, well-drained soils and periodic flooding.

A clearer understanding of the soil and plant selection implications in an urban Mediterranean climate context has consequences for rain garden implementation beyond the Bay area. While the Water Framework Directive recommends that stormwater be dealt with at the source, the EU and particularly the Mediterranean member states lag in rain garden implementation. The EU Flood Directive (2007) similarly pushes for strategies that will reduce and manage the risk of floods. Both directives set firm objectives for water quality and flood safety standards, respectively, leaving the implementation to local and regional control. This approach is highly compatible with the implementation of rain garden and other forms of bioretention that represent small-scale local and regional strategies, with the potential for cumulative effects. In the U.S., water quality regulations drive rain garden implementation at the regional scale (Eisenstein, 2009). This is particularly evident in the Chesapeake Bay region, as well as in the Pacific Northwest. A similar process of regional and local rain garden implementation is possible in the EU, in response to the WFD's establishment of broad, yet firm water quality standards.

<u>Figures and tables</u>

Figure 1. Single-ring infiltrometer, under falling head

Table 1. Rain garden soil specifications

Authority + preferred soil type	Infiltration rate (in/hr)			Soil Media Recommendations						
				TOP SOIL	SAND				LARGER	COMPOST
				CLAY + SILT	Very fine	Fine	Medium	Coarse	PARTICLES	
	Min	Optimum	Max	< .05	.05 -.15	.15 - .25	.25 - 1.0	1 - 2.0	2.0 - 3.4	← particle sizes (mm)
Alameda Co. loamy sand	5	---	10 Emeryville: 50	10% <5%	85% construction sand				---	5%
Contra Costa Co.	5	---	50	10 - 20%		Mix A 50 - 60% Mix B 60 - 70%				30 - 40% 30 - 40%
Sonoma Co. sandy loam	5		10	clay 0-20%; 0-28% silt	43 - 84% sand					
FAWB	4	4 to 12	24	< 3%	5 - 30%	10-30%	40 - 60%	7-10%	< 3%	

Table 2. Surveyed sites names, type of rain garden implemented and drainage source.

Project name	Type of raingarden	Drains
Emeryville Station East	sub-grade planter	roof run-off
Glashaus	sub-grade planter	courtyard
Google Day Care	swale planter strip	parking lot
Mint Plaza	at-grade plaza planter	plaza
Muir Labs	above-grade planter	roof run-off
Senior Center, Dublin	swale planter strip	parking lot
Shanon Center, Dublin	sub-grade planter	plaza
Shotwell Greenway	at-grade planter	sidewalk
West Elm	above-grade planter	roof run-off

Table 3. Uncorrected infiltration rates measured in situ.

	Infiltration time			
Project Name	Rep 1 (sec)	Rep 2 (sec)	Average (sec)	Average infiltration rate (in/hr)
Emeryville Station East	72	93	82.5	54.11
Glashaus	274	302	288	15.50
Google Day Care	361	288	324.5	13.76
Mint Plaza	111	92	101.5	43.98
Muir Labs	1210	877	1043.5	4.28
Senior Center, Dublin	119	192	155.5	28.71
Shannon Center	109	114	111.5	40.04
Shotwell Greenway	935	540	737.5	6.05
West Elm	329	875	602	7.42

Table 4. Corrected infiltration rates. See Appendix 1 for calculations.

Project Name	Corrected average infiltration rate (in/hr)
Emeryville Station East	45.04
Glashaus	12.90
Google Day Care	21.92
Mint Plaza	36.61
Muir Labs	3.56
Senior Center, Dublin	23.90
Shannon Center, Dublin	33.33
Shotwell Greenway	5.04
West Elm	6.17

Figure 2

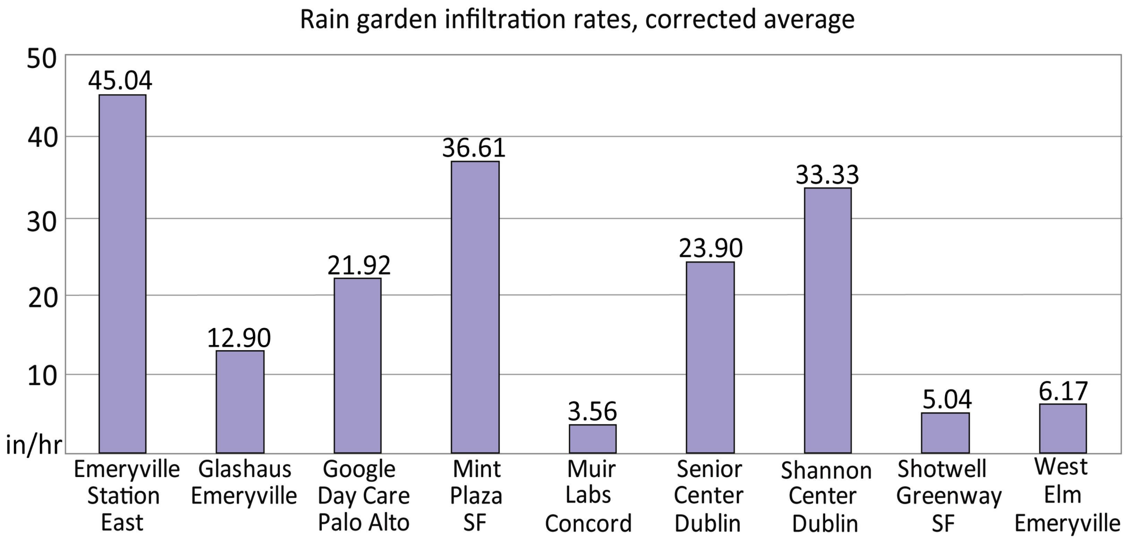


Figure 3

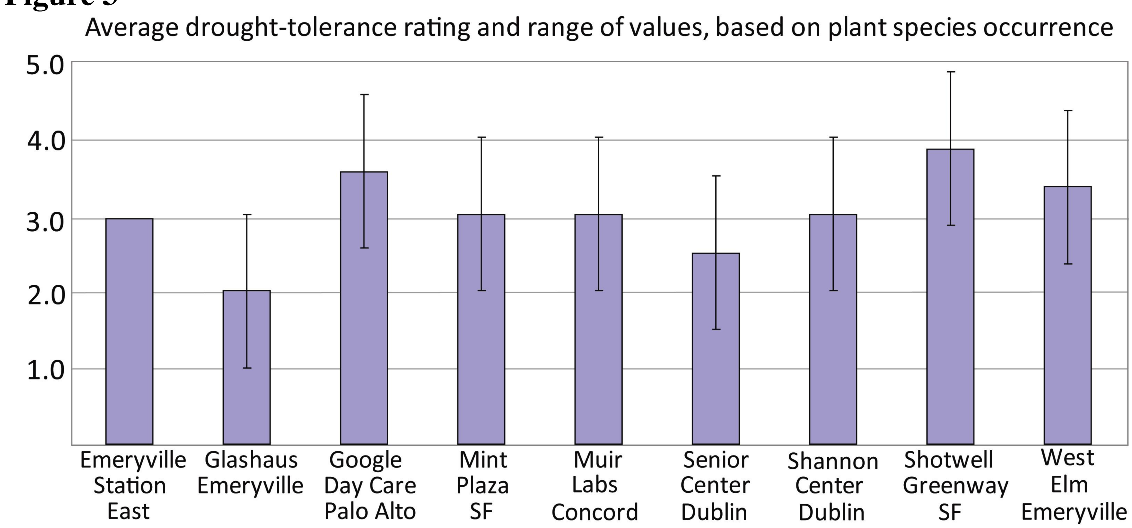


Figure 4

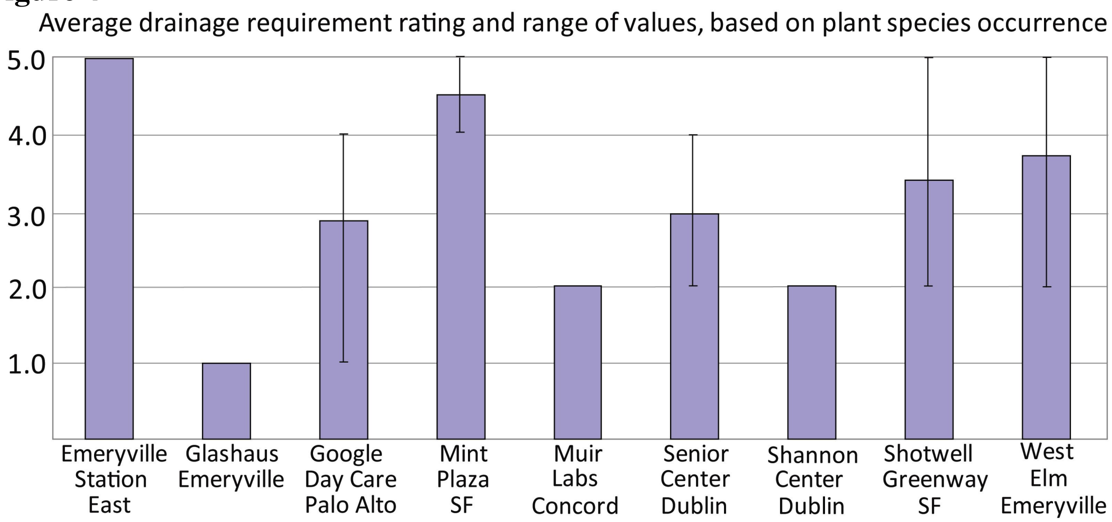


Table 5

Project Name	Plant species
Emeryville Station East	*Chondropetalum tectorum*
Glashaus	*Juncus*
Google Day Care	*Achillea, Artemisia, Avena, Iris, Juncus, Pilularis, Sycamore x racemosa,*native bunch grass
Mint Plaza	*Chondropetalum, Heuchera*
Muir Labs	*Acer, Nandina, Trachelospermum*
Dublin Senior Center	*Acer palmatum, Cercis, Geranium, Pittospurum*
Shannon Center, Dublin	*Dietes, Pyrus*
Shotwell Greenway	*Agave, Citrus, Crassula, Cryophytum, Dietes, Euphorbia, Festuca, Gazania, Lavandula, Phoenix, Phormium, Stachys*
West Elm	*Eriodictyon, Fragaria, Nemophila, Penstemon, Polystichum, Ribes, native bunch grass*

Table 6

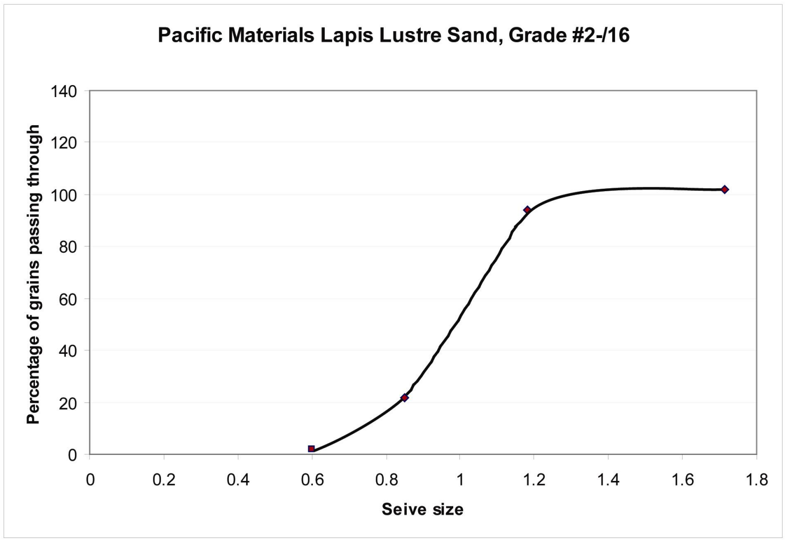
Common name	Scientific name	Drought-tolerance rating	Drainage requirements
Japanese maple	*Acer palmatum*	1	3
Cretan maple	*Acer sempervirens*	3	2
Maple	*Acer sp.*	2	2
Yarrow	*Achillea millefolium*	3.5	4
Agave	*Agave*	5	5
Wormwood	*Artemisia*	4	4
Wild oat	*Avena*	4	0
Western redbud	*Cersis occidentalis*	3	4
Cape rush	*Chondropetalum tectorum*	3	5
Lemon	*Citrus limon*	3	3
Crassula	*Crassula*	5	5
Ice plant	*Cryophytum crystallinum*	5	0
Fortnight lily	*Dietes sp.*	4	2
Yerba santa	*Eriodictyon glutinosum*	4	4
Euphorbia	*Euphorbia*	3.5	4
Blue fescue	*Festuca glauca*	3.5	4
Strawberry	*Fragaria*	1	5
Gazania	*Gazania*	3.5	2
Geranium	*Geranium*	3	0

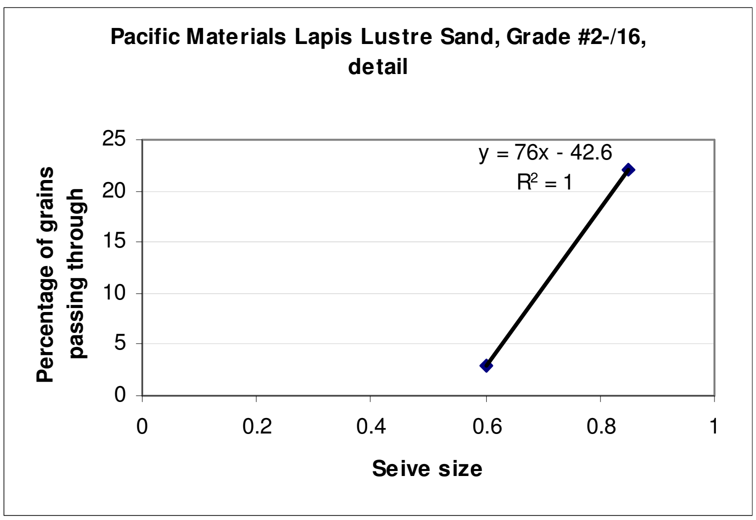
Choral bells	*Heuchera*	3	4
Doug iris	*Iris douglasiana*	4	4
Rush	*Juncus*	2	1
Lavender	*Lavandula*	4	4
Heavenly bamboo	*Nandina domestica*	4	0
Nemophila	*Nemophila menziesh*	4	2
Beard tongue	*Penstemon*	4	5
Canary Island date palm	*Phoenix canariensis*	3.5	2
New Zealand flax	*Phormium tenax*	3	3
Coyote brush	*Pilularis*	4	2
Mock orange	*Pittosporum*	3	2
London plane tree	*Platanus x racemoa*	3	2
Western sword fern	*Polystichum munitum*	2.5	3
Bradford pear	*Pyrus calleryana*	2	2
Currant/gooseberry	*Ribes*	3	4
Lamb's ear	*Stachys byzantina*	3	3
Star jasmine	*Trachelospermum jasminoides*	4	2
Native bunch grass		5	3

Table 6, continued

Drought-tolerance rating system	**Drainage-tolerance rating system**
	0 = no preference
1= ample water	*1= grows well in standing water*
2= ample to moderate water	*2= grows in poorly drained soil*
3= moderate water	*3= grows in moderately drained soil*
4= low water	*4 = grows in fast draining soil*
5= minimal to no water	*5 = grows only in very well-drained soil*

Appendix 1. Calibration of field infiltrometer methods.





Hazen's effective size = D10 = 0.68mm= 0.068cm

k = 100 (D10)(D10)

cm/sec	cm/hr	in/hr
0.4624	1664.64	**655.37**

Infiltrometer test

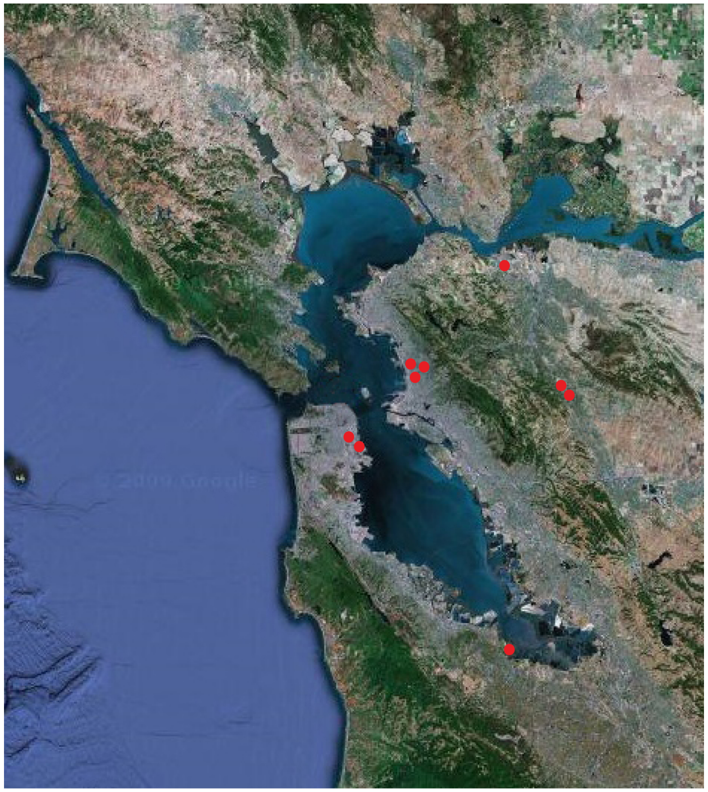
column height (in)		infiltration rate (sec)	infiltration rate (sec)	infiltration rate (in/hr)
3.35	rep 1	16	0.209375	753.75
3.35	rep 2	15	0.223333	804
3.35	rep 3	15	0.223333	804
			Average	**787.25**

Correction coefficient = 655.37 ÷ 787.25 = 0.8325

Appendix 2. Project name, location and source/contact.

Project Name	Address	Source/Contact
Emeryville Station East	59th + Hollis, Emeryville	Peter Schultze-Allen, Environmental Analyst, Public Works Dept., Emeryville
Glashaus	65th + Hollis, Emeryville	Peter Schultze-Allen, Environmental Analyst, Public Works Dept., Emeryville
Google Day Care	3801 E. Bayshore, Palo Alto	Lance Takehara, Sandis Civil Engineers
Mint Plaza	54 Mint Street, SF	Ken Kortkamp, PE, Sherwood Design Engineers
Muir Labs	Commercial Circle + Bates Ave, Concord	Lance Takehara, Sandis Civil Engineers
Senior Center, Dublin	7600 Amador Valley Boulevard	Mark Lander, City Engineer, City of Dublin
Shanon Center, Dublin	San Ramon Rd + Shannon Ave., NW corner	Mark Lander, City Engineer, City of Dublin
Shotwell Greenway	Shotwell b/t 17th + 18th, SF	PlantSF
West Elm	Shellmound + Bay St., Emeryville	Peter Schultze-Allen, Environmental Analyst, Public Works Dept., Emeryville

Appendix 3. Project locations.



Appendix 4. Project images

Emeryville Station East, Emeryville

Google Day Care, Palo Alto

Glashaus, Emeryville (Photo credit, SF PUC)

Mint Plaza, San Francisco

Muir Labs, Concord

Senior Center, Dublin

Shanon Center, Dublin

Shotwell Greenway, San Francisco West Elm, Emeryville

Shotwell Greenway, San Francisco

Acknowledgments

Multiple individuals generously contributed their time and expertise to this project. Evan Variano, CEE UC Berkeley, provided help with and materials for the development of calibration methods. Peter Schultze-Allen, environmental analyst for the City of Emeryville, answered numerous emails about Emeryville rain garden sites. Lance Takehara of Sandis Engineers informed me about the Google Day Care site and answered many of my questions about rain garden implementation in the Bay Area. Ken Kortkamp, Sherwood Design Engineers, provided information about the Mint Plaza site. Mark Lander, Dublin City Engineer, assisted with the selection of Dublin sites, answering many of my questions in the process. PlantSF provided information about the Shotwell Greenway site. Matt Kondolf, Juliet Christian-Smith and Rafi Silberblatt assisted in the development of the research question, methods and manuscript.

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