Title

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Abstract

Stormwater biofilters (also called rain gardens, bioretention systems, and bioswales) are used to manage stormwater runoff in urbanized environments. Some benefits of biofilters include flood prevention, stormwater runoff water quality improvement, and wildlife habitat. This technology has been implemented on a larger scale in southeast Australia, but cities and counties in southern California just beginning to construct biofilter systems to manage stormwater runoff. Biofilters tend to be larger in southern California than in southeast Australia. Differences in rainfall patterns likely affect biofilter function. Southern California has much longer periods between rain events than southeast Australia, providing challenges to establishing and maintaining vegetation in biofilters. The use of biofilters for restoring pre-development flow regimes has been studied in a peri-urban watershed in southeast Australia, but flow regime restoration is not likely in highly urbanized locations in both Australia and southern California. However, stormwater runoff treatment and harvesting in decentralized biofilters could substantially reduce storm flows and improve water quality in receiving waters while improving urban water supply and extending the life of existing stormwater management infrastructure.

Keywords: stormwater biofilters, water quality, stormwater harvesting, green infrastructure, low impact development, rain garden, bioswale, urban runoff

Introduction

Urban stormwater management is important for controlling pollution and flooding associated with runoff from impervious surfaces following rain events but has often been at the cost of important ecosystem services and functioning in urban streams (i.e., the urban stream syndrome)[1]. Low Impact Development or Green Infrastructure stormwater systems that infiltrate water through a vegetated filter media can be used to capture and treat urban stormwater runoff and re-establish pre-development flow patterns[2]. In this paper, we will refer to these systems as stormwater biofilters, but recognize that they also capture and treat dry-weather runoff not associated with storms. There are many similarities in design criteria of bioswales, vegetated strips, rain gardens, and bioretention or biofiltration systems; we are considering the term "biofilter" to encompass all systems that filter stormwater runoff through a vegetated filter media and convey treated stormwater into perforated pipes leading to a discharge pipe and/or percolate into the underlying soil. Biofilters remove pollutants such as metals, solids, oils and grease, nutrients, and pathogens through a myriad of physical, physicochemical, and biological processes. All of these processes occur as a result of gravity-fed hydraulics, filter media characteristics, and capturing sunlight through photosynthesis, making these systems low-energy options for stormwater management. Biofilters are employed in stormwater management in a variety of regimes. Currently, many cities in the United States and Australia offer rebate programs and guidance documents to design and construct biofilters at residents' homes. Government and non-profit organizations are also building biofilters at the single project- and neighborhood-scale. Typically, single projects capture runoff from parking lots or a large commercial or industrial development; these projects are commonly constructed by private companies who own the lots from which stormwater is collected. Neighborhood-scale projects aim to manage larger catchments and often include several types of stormwater management technologies; these projects are commonly constructed by government agencies, often in collaboration with other organizations, and are more extensive and expensive.

Comparing US and Australian stormwater management infrastructure is useful because both developed countries are mitigating the effects of urban stormwater runoff on aquatic ecosystems using low impact development[3]. In this paper, we compare the implementation of stormwater biofilters in southeast Australia and southern California. Although stormwater biofilters have been constructed in both of these regions, they differ in the motivations behind their construction. We discuss these motivations as well as differences in the climates of the two regions, design and maintenance of biofilters, and the ecology of biofiltration systems. We show how the different environmental settings could influence optimal implementation in each region, although little work has been done so far to identify the optimal implementations.

IMPETUS FOR IMPLEMENTATION

In southeast Australia, a major impetus for the construction of stormwater biofilters was water conservation in response to the so-called Millennium drought[4]. Additionally, stormwater biofiltration was recognized as an effective method to prevent nitrogen from reaching Port Phillip Bay because these systems can handle the variable concentrations and flows of runoff events[5, 6]. The major water purveyor, Victorian state statutory authority Melbourne Water, adopted policies and incentives to encourage large-scale implementation of stormwater biofilters. Melbourne Water programs include a "Ten Thousand Rain Garden" program. In addition, studies by Melbourne scientists had demonstrated an adverse effect of stormwater runoff from urbanized watersheds[1]. Besides the active support of Melbourne Water, regulatory requirements encourage the construction of stormwater biofilters. New developments and redevelopments are required to manage stormwater according to Clause 56.07-4 of the Victoria Planning Provisions (http://planningschemes.dpcd.vic.gov.au/schemes/vpps/56_07.pdf). The involvement of academic scientists in Melbourne is also noteworthy. The Water for Liveability Centre at Monash University has played a central role developing the scientific foundations for biofilter construction and the implementation of actual projects. The Little Stringybark Creek Project is a collaborative research program where researchers from Monash University and University of Melbourne have investigated the potential of watershed-scale impact of managing stormwater runoff with biofilters and rainwater harvesting. This project is the largest of its kind in the world and has so far resulted in the construction of dozens of biofilters.

In southern California, the impetus for stormwater biofilter implementation has been control of water pollution under the federal Clean Water Act. Initially, the State Water Resources Control Board (SWRCB) promulgated regulations requiring stormwater be retained on new construction sites. Under the 2009-0009-DWQ Construction General Permit, stormwater runoff originating in new developments in California was recognized as point source pollution and regulated under the Clean Water Act. The Clean Beach Initiative, a fund under California's SWRCB, provided funding to projects aimed at reducing fecal indicator bacteria (FIB) loads to California's beaches from urban runoff[7]. Stormwater biofilters were suggested as a best management practice (BMP) to preserve drainage in urban areas and prevent FIB from reaching beaches. These stormwater biofilters (among other techniques for retaining stormwater) were largely constructed by permittees on private property. More recently, Municipal Separate Storm Sewer System (MS4) regulations have led to broader adoption of stormwater biofilters. Stormwater biofilters constructed by government agencies are typically larger, more expensive, and may include other stormwater management techniques such as infiltration galleries and pervious pavement. Most neighborhood-scale systems have been built by local government agencies. The Elmer Avenue Green Street project, coordinated by a consortium including the City of Los Angeles, the Council for Watershed Health and TreePeople (non-profit organizations), mitigated flooding in a Sun Valley neighborhood by capturing runoff in a large infiltration gallery installed beneath Elmer Avenue[8]. This project also included the construction of 24 street-side biofilters and rainwater harvesting tanks. The California Department of Transportation (CalTrans) constructed a biofilter in 2006 as part of a pilot project to investigate the suitability of using this technology as a BMP for stormwater management. Monitoring of the treatment performance and maintenance requirements of the CalTrans biofilter is ongoing. There has been limited engagement with the academic community in the role of biofilter implementation in southern California.

DIFFERENCE IN CLIMATE

Southeast Australia and southern California also differ in their climate, which may have a substantial impact on biofilter performance. Southeast Australia is considered a temperate climate while southern California has a Mediterranean climate. Temperatures are similar, with mean monthly high temperatures in Melbourne and Los Angeles varying from 15-27°C and mean monthly low temperatures varying from 7-17°C (Figure 1). Los Angeles is slightly warmer, with both average high and low temperatures about 4°C higher in the winter and average low temperatures about 2^{o}C higher in the summer. Los Angeles also has slightly more consistent monthly mean high temperatures, with a 6^{o}C difference between winter and summer compared to a 12^{o}C difference in Melbourne.

In contrast to relatively consistent temperature patterns, the rainfall patterns of southeast Australia and southern California differ dramatically. Mean monthly rainfall in Melbourne varies only between 4 and 6 cm (Figure 2). In contrast, mean monthly rainfall in Los Angeles varies between 0 and 12 cm, with 80% of the rain falling in December to March. As a result, there are much longer periods without rain in Los Angeles. This difference is apparent in the frequency of antecedent dry days (ADD), defined as the number of days preceding a rain event over 1 mm/day. Between 1994 and 2013, periods of ADD over 30 days occurred 51 times in Los Angeles but only 3 times in Melbourne (Figure 3). In Melbourne, the pattern of ADD was similar in the driest and wettest years over the 20-year period examined, even though rainfall differed by a factor of two. In contrast, the driest and wettest years in Los Angeles had distinctly different ADD distributions, with widely spaced rainfall during the driest year. The more consistent rainfall in southeast Australia means shorter periods of dry weather, which can influence biofilters performance. Besides longer periods of dry weather in Los Angeles, there are larger differences from year to year, meaning that there are more years when biofilters would receive only sporadic rainfall. Nitrogen and metals removal efficiencies are reduced by biofilter drying[9, 10]. In addition, a saturated or submerged zone, which can improve nitrogen and metals removal[10], would be easier to maintain consistently with regular rainfall. Because of the extended dry periods, a saturated zone likely could only be maintained year-round in southern California if there was considerable dry-weather runoff or if it was replenished with potable water. Although biofilter drying generally reduces pollutant removal efficiency for many pollutants and can challenge the maintenance of a biofilter, prolonged dry periods enhanced the removal of micropollutants[11].

Stormwater pollutant loads differ somewhat between southeast Australia and southern California, and this could influence biofilter performance or which design would be optimal in each location. In both regions, pollutant loads range widely for every constituent (Table 1), although there are some general patterns. Nutrients tended to be higher in southern California stormwater. Although there was broad overlap, total suspended solids ranged higher in southeast Australia stormwater. Lead and *E. coli* also ranged higher in southeast Australia stormwater. These data reflect stormwater runoff, which reflect inflow after rain events but may not represent dry weather runoff pollutant loads.

DESIGN SPECIFICATIONS AND MAINTENANCE

There are differences in key design characteristics of stormwater biofilters in southeast Australia and southern California. We compared 13 Victoria and 13 southern California stormwater biofilters (Table 2). These biofilters represent various ages, sizes, and designs of the major neighborhood-scale biofilters found in Victoria and southern California. Most biofilters in southern California were constructed in the past four years, while Victoria biofilters have been built steadily over the past ten years. The biofilters in both regions cover a wide size range, but southern California biofilters were not as small as many of the Victoria biofilters, and three of the southern California biofilters were larger than any of the Victoria biofilters. The mean biofilter size in southern California was 646 m^2 while the mean size in Victoria was 160 m^2.

Catchment areas also differed somewhat between the two regions. Eight of the 13 Victoria biofilters drained catchments of less than 1 ha compared to only one southern California biofilter. Both regions included one project greater than 50 ha. The mean catchment areas of southern California and Victoria biofilters were 10 ha and 7 ha, respectively, while the median areas were 5.0 ha and 0.43 ha. Catchment ratio (biofilter area/impervious catchment area) has been used as an indicator of biofilter effectiveness on a catchment scale, with Australian researchers suggesting that biofilters should cover 2% of the impervious catchment area for optimal performance[12]. Southern California BMP guidelines suggest designing biofilters to infiltrate the runoff from a 2-cm (¾-in) storm event within the drainage area within 48 hours[13]. Sizing calculations include percolation rates of filter media and underlying soils, impervious surface area, and the runoff coefficients for drainage areas[13]. Four Victoria and four southern California biofilters reach the Australian catchment ratio target. All but one of the Victoria biofilters were located in residential areas (the exception is located in an industrial and commercial area, while seven southern California biofilters were in commercial districts (two combined with industrial and one combined with residential, Table 2).

Biofilters designed for infiltration are not lined with an impermeable layer, allowing treated water to flow vertically to the underlying soil, potentially recharging groundwater. Biofilters with underdrains can be lined or unlined. These biofilters contain slotted or perforated pipes plumbed to flow to the adjacent stormwater conveyance system or receiving stream (or potentially to be captured for use in irrigation or other purposes). Underdrains can be designed with outflows at an elevation higher than the bottom of the biofilter in order to retain water between inflow events, which results in a submerged zone. Almost all biofilters in both regions were designed for infiltration (Table 2). In Los Angeles, three biofilters had underdrains as well as infiltration, and again two were underdrain alone. In Melbourne, seven biofilters had underdrains as well as infiltration, and two were underdrain alone. Hereford Road Raingarden has both types of flow regimes, providing groundwater recharge via infiltration during most rain events and flood protection with underdrains during larger rain events by preventing high ponding (Sidebar 1).

We classified biofilters as curb cutouts or standalone systems to make comparisons between their immediate surroundings. Curb cutout biofilters are systems located adjacent to the street and sidewalk (Figure 4a). These biofilters may be required to adhere to certain regulations set by transportation agencies regarding visibility, safety, and connectivity to the stormwater conveyance system. The City of Los Angeles provides standard plans that identify plant type, ponding depth, and dimensions required to comply with local regulations[13, 14]. Similarly, Melbourne Water provides engineering plans for biofilters and other green infrastructure that provides guidance to comply with local regulations[15]. Standalone biofilters refer to systems not located between a street and sidewalk. These systems are typically in public parks or easements (Figure 4b). Typically, standalone biofilters have more flexibility in design, but could have restrictions based on safety if they are located in a public area, particularly regarding plant type and ponding depth. One of the Ballona Creek Rain Gardens is located between a bike path and residential area (Sidebar 2). This biofilter infiltrates runoff that would otherwise flow directly into Ballona Creek. This long, narrow design would not likely be possible with other types of stormwater management systems. Both Melbourne and Los Angeles had 7 curb cutout biofilters. Only Los Angeles had parking lot biofilters (2), with the remainder in both regions being standalone.

A submerged (saturated) zone can lead to more consistent biofilters performance. Maintaining a submerged zone led to stable hydraulic performance during prolonged wet and dry periods, while the outflow rate of biofilters with no submerged zone was reduced during prolonged wet periods[11]. Submerged zones have been shown to enhance removal of nitrogen[16-19] and heavy metals[20]. Theoretically, a submerged zone could increase plant survivorship by allowing plant roots to have access to water for an extended period of time. However, we are not aware of any studies documenting this potential, nor evaluating its importance for different species. The presence of a submerged zone could influence the plant species used in a biofilter, both in terms of pollutant removal and long-term maintenance. Again, we know of no studies evaluating these aspects; the major study evaluating the influence of plant traits on biofilter performance[21] did not evaluate submerged zones. Because of the difference in the frequency of antecedent dry days, submerged zones would be easier to maintain in southeast Australia than in southern California. In southern California, submerged zones would likely require supplemental water to maintain them through the dry season unless dry-weather runoff was substantial. In some settings, such as golf courses, it might be possible to direct runoff to biofilters to maintain submerged zones. Similarly, greywater from commercial or residential buildings could be treated using biofilters while providing water for maintaining submerged zones. Alternatively, submerged zones could be allowed to dry out and then be re-established following storm events. Submerged zones are beginning to be incorporated into stormwater biofilters in Melbourne, but are not currently being used in southern California.

Plants represent critical features of stormwater biofilters, but there are relatively few design guidelines available. In both regions, native plants are recommended[13, 15]. In Los Angeles, standard plans for curb cutout biofilters include only plants with mature heights below 91 cm (3 ft) in order to maintain sight lines, but offer no guidance on planting densities[14]. In southern California, plants are often (but not always) selected by landscape architects, apparently with little knowledge of their performance in stormwater biofilters. In southeast Australia, research on the biofilter performance of native plants[21] has provided some information for plant selection, though this has not necessarily been followed. For example, the single species with the best pollutant removal performance, *Carex appressa*, is rarely used in Melbourne stormwater biofilters, possibly because of its sharp leaves. There is a need for more information about the performance of native species, especially in California, more complete consideration of all relevant plant traits, including aesthetics and maintenance considerations as well as pollutant removal, and better incorporation of these considerations into the selection of plants for a particular biofilter system.

In southern California, larger systems are typically maintained by the agency responsible for construction. Procedures include removing undesired vegetation, trash and debris, accumulated sediments, and residue from oils and grease; replanting desired vegetation as needed; re-leveling eroded areas and filling rutted areas with gravel; and observing performance under wet conditions[13]. Biofilters in southeast Australia are similarly maintained with the exception of irrigation following plant establishment. Additionally, the top 2 – 5 cm of filter media is scraped off every few years in some Australian biofilters in order to maintain hydraulic conductivity and remove heavy metals, as suggested by Hatt et al.[22]. Responsibility for the maintenance of smaller systems in southern California, such as curb cutouts, is less clear. Initial maintenance may be performed by the agency constructing the biofilters, with subsequent maintenance the responsibility of the landowner. Transferring maintenance responsibility might be attractive to government agencies; however, distributing responsibility among many parties can be problematic because differing levels of maintenance can occur.

Because of the large number of variables influencing stormwater biofilter performance, specifying a single optimal design would be difficult. One study from Melbourne specifically addressed this problem, concluding that the optimally designed biofilter is at least 2% of its catchment area and possesses a sandy loam filter media planted with *Carex appressa* or *Melaleuca ericifolia*[12]. Although a good start, this study has limitations, including the fact that it was conducted in laboratory columns and did not evaluate the performance of species combinations. No similar study evaluating optimum biofilter design has been conducted for southern California. Besides the need to evaluate California native plant species, there may be other differences between southeast Australia that need to be considered in southern California biofilter design. For example, Australian plants are adapted to low levels of soil nutrients, particularly phosphorus, so sandy loam may be more suitable there than other regions[12]. In other areas with different design criteria, catchment coverage of 5% to 10% has been estimated to be required to meet phosphorus reduction targets based on modeling studies[23]. There have been very few field-based evaluations of biofilter performance in southeast Australia (but see [9, 24-26]) or southern California. Most field studies of biofilter performance have been undertaken in North Carolina[27-32] and Maryland[33-36].

Although biofilters have the potential to harvest stormwater (or other runoff) to increase water supply, few biofilters in southeast Australia or southern California have been constructed to take advantage of this potential. One exception is Edinburgh Gardens biofilter in Fitzroy North, VIC, AU. Stormwater runoff is collected from the surrounding the residential area, filtered through the 600-m^2 biofilter, and stored in an underground tank. Harvested and treated runoff provides 50% of the water needed for irrigating this 24-ha park (http://www.yarracity.vic.gov.au/environment/Parks-and-reserves/Edinburgh-Gardens/Proposed-Raingarden/).

ECOLOGY OF BIOFILTRATION SYSTEMS

A biofilter ecosystem consists of the physical elements, plants, animals, and microbial community. Most studies of stormwater biofilters have focused on physical elements, particularly the media used and its arrangement within the biofilter. Much less has been published about the biological elements of biofilters. Of these, by far the most work has been done on plants. Vegetated biofilter mesocosms removed more nutrients than unvegetated mesocosms[37, 38]. Read et al. have examined the role of different plant traits in stormwater biofilter performance using laboratory mesocosms[21]. The strongest contributors to N and P removal were related to root extent, with the plants associated with the highest pollutant removal, e.g., *Carex appressa*, combining these root traits with high growth rates. Assimilation by plants has been shown to be the primary mechanism for removing nitrate under typical stormwater conditions[39]. Plants can be important in maintaining hydraulic conductivity in stormwater biofilters[9]. Le Coustumer et al. found that species with thick roots, such as *Melaleuca* spp., were able to maintain high hydraulic conductivity over time; they argue that the choice of plant species is a key design element because of the potential maintenance of system hydraulics[40].

Studies to date have focused on plant species from southeast Australia. Although general plant traits (such as extensive root systems or thick roots) may lead to similar stormwater biofilter performance in southern California, this has yet to be tested; we are currently conducting mesocosm experiments to evaluate these factors using native southern California plants. Although the results of these experiments are not yet available, there are some differences between southeast Australia and southern California that are apparent. It is critical that plant species used in stormwater biofilters be well adapted to the local conditions, and as noted above the precipitation regimes are markedly different between southeast Australia and southern California. Because of frequent rainfall throughout the year, plants in southeast Australia stormwater biofilters can more easily survive without supplemental water, particularly if a submerged zone is incorporated into the biofilter design. In contrast, plants in southern California biofilters should be able to withstand an extended dry period; although it is possible to provide supplemental irrigation, this is not desirable, particularly with the current and projected shortage of water in southern California[41]. Although wetland plants are frequently considered for planting in biofilters, in southern California biofilters will be "wet" for only a relatively short period of time, so plants will need to tolerate saturated conditions separated by dry conditions[42]. Therefore, native terrestrial plants (from chaparral, coastal sage scrub, or grasslands) might be more appropriate for southern California biofilters, although these species have not yet been evaluated. In their review, Houdeshel et al. suggest planting deep-rooted shrubs that do not require irrigation following establishment in arid climates but do not provide information on biofilter performance[43].

To date, very few of the plant species native to southeast Australia and southern California have been tested for biofilter performance, or even planted in biofilters. Both of these regions have rich native flora, with more than 800 endemic plant species in southern California[44] and more than 1800 indigenous plant species in the Melbourne area[45]. The most extensive investigation to date of plants for use in biofilters evaluated 20 plant species[21], so clearly there are many candidate species that have not yet been studied. Both regions also include many non-native invasive plant species. Biofilters in both regions could be particularly prone to colonization of invasive species due to the higher moisture and nutrient content than surrounding soils and receiving seeds from runoff. Managers of biofilters in both regions have noted that weed suppression has a high maintenance cost.

Besides the identity of species planted, southeast Australia and southern California may have different planting schemes, particularly in the mix of species planted in individual biofilters. However, no studies have systematically evaluated the plant communities in stormwater biofilters in either region. We are currently conducting these studies.

In contrast to the number of studies on the role of plants in stormwater biofilters, very little work has been done on animals and microbes. Earthworms and other burrowing terrestrial macroinvertebrates have the potential to affect the hydrology by creating macropores in the filter media[46]. These animals could also affect nutrient cycling by providing an anaerobic environment in their guts capable of denitrification of soil nitrate and through providing a conduit to the surface through macropores[46]. Additionally, the interaction between plants and animals in biofilters and the consequences in function have not been examined[47].

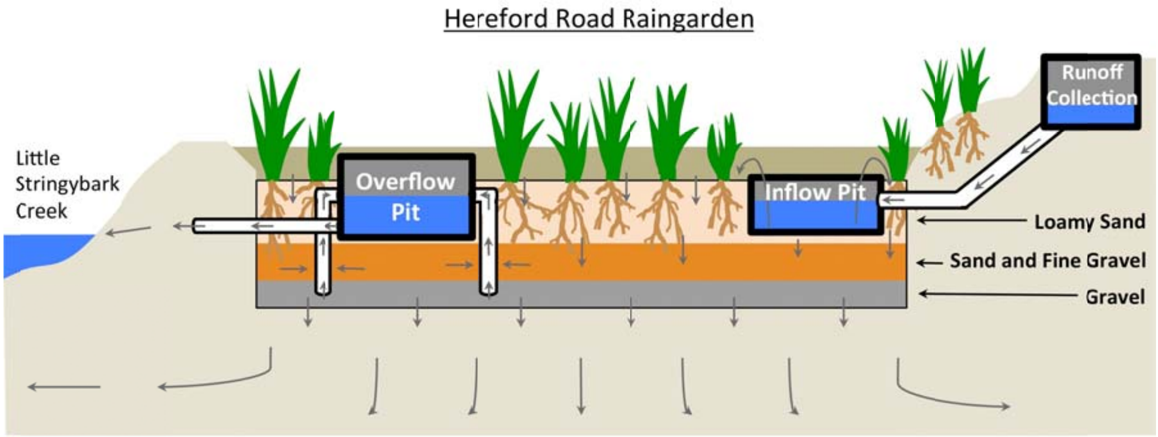
The role of the microbial community in stormwater performance is acknowledged, but few details have been studied. For nitrogen removal, the importance of microbially mediated denitrification is recognized[48], and conditions supporting increased denitrification, particularly a submerged zone, identified[17, 19]. Although some studies of specific microbes, or expressed genes, have been conducted, these focus narrowly on nitrogen transformations[49] rather than a broader ecological roles of the microbial community (e.g., mycorrhizae supporting plant growth and diversity, competition between denitrifying bacteria and plant roots for nitrate).

As biological elements in an urbanized landscape, biofilters can provide important ecological values and ecosystem services. This benefit of biofilters has received little attention, but particularly as more biofilters are constructed in a catchment, their ecological influence will become more important. Stormwater biofilters are explicitly designed to provide several important ecosystem services, including flood attenuation, groundwater recharge and water quality improvement. However, they may also provide other ecosystem services for which they have not been explicitly designed (at least to date). One documented ecosystem service provided by stormwater biofilters is the support of biodiversity. Stormwater biofilters support a higher diversity of aboveground terrestrial invertebrates than surround gardens and lawns[50]. Kazemi and co-workers have argued that transitioning from traditional urban landscapes such as lawns to biofilters would enhance urban biodiversity[10, 50, 51]. Few studies have evaluated stormwater biofilter characteristics that would increase the support of biodiversity, but Kazemi et al. have suggested that greater leaf/plant litter depth and higher plant species richness contribute to increased biodiversity in biofilters[52]. Kazemi's studies were conducted in Melbourne; although the results may apply to southern California, no similar studies have yet been conducted there.

Other ecosystem services that may be performed by stormwater biofilters include carbon sequestration[53], pollinator habitat[50], aesthetics, and potentially water supply[2]. Constructing biofilters with underdrains connected to stormwater harvesting tanks or infiltration-type (unlined) biofilters could help restore pre-development flow regimes in smaller watersheds[2]. Biofilters can artificially recharge groundwater when underlying soils have adequately high infiltration rates[54]. This recharge could be beneficial if the biofilter area is sufficient, soil pollution and depth to groundwater are low, and the increased water table does not adversely affect infrastructure belowground.

Sidebar 1: The Hereford Road Raingarden

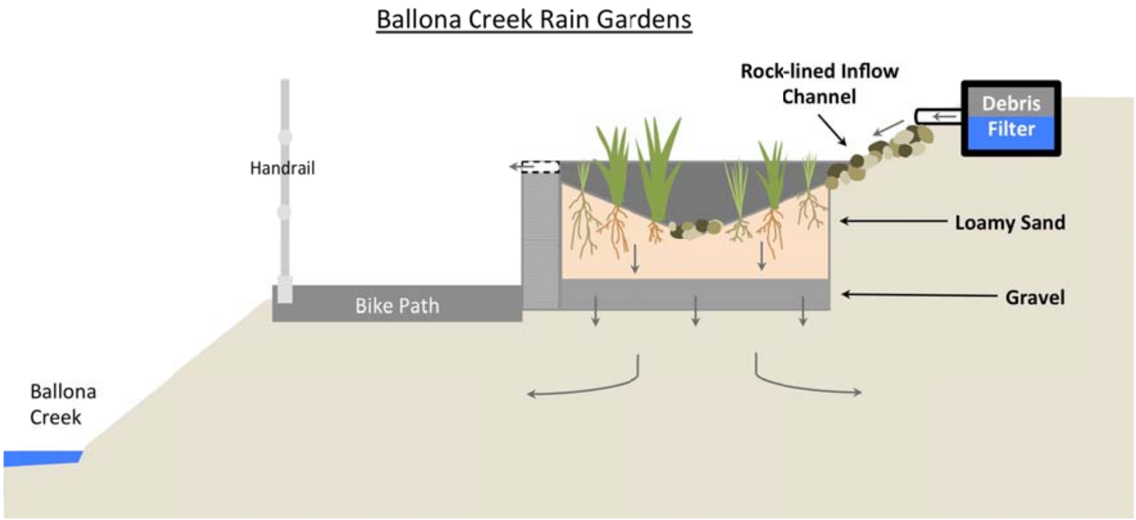
The Hereford Road Raingarden was constructed in 2010 to replace a stormwater retention basin in an area adjacent to Hereford Rd. and a petrol station. This 100-m^2 stormwater biofilter treats runoff from a 9,300-m^2 drainage area in residential Mt. Evelyn, VIC, AU. A sand transition layer and gravel drainage layer allow water to infiltrate into underlying soils or is collected in perforated pipes flowing first to an overflow pit, then to Little Stringybark Creek. The loamy sand layer is the filter media where most plant roots occupy. Hereford Road Raingarden is planted with species that have been reported to promote high treatment performance: *Carex appressa, Juncus flavidus,* and *Melaleuca* sp. This biofilter was constructed as part of a catchment-scale effort to restore the Little Stringybark Creek (LSC) stream ecosystem through flow-regime management. Infiltration and collection pipes prevent stormwater runoff from entering Little Stringybark Creek directly during low-flow events and provide flood protection during high flow events.



Sidebar 2: The Ballona Creek Raingardens.

The Ballona Creek Raingardens were constructed in 2012 to filter runoff from residential, commercial, and industrial areas in Culver City, CA, US before infiltrating into the underlying soil. Two biofilters (810 m^2 and 1,900 m^2) were constructed to filter runoff from 5 ha of residential area (810-m^2 biofilter) and 5 ha of industrial/commercial area (1,900-m^2 biofilter). Biofilters were sized to capture and infiltrate 2.5 cm of rain over 24 hours. Stormwater runoff enters a debris trap before flowing over a rock-lined channel into the 8-m wide biofilters filled with a sandy loam filter media sloped at a 3:1 ratio to pond water and channel flow. Overflow pipe conveys water to Ballona Creek. Grasses and sedges are the dominate the plant community in these rain

gardens. Volunteers from the community remove non-native species annually. The debris filter will be cleaned every 3 years.



Box 1: Key differences between biofilters in southeast Australia and southern California.

- Climatic differences dictate vegetation choice and hydraulic design. More drought tolerant plant species are expected in southern California biofilters. Ponding zones are generally deeper in southern California biofilters.
- Most southern California systems are curb cutouts or located in parking lots. More biofilters in southeast Australia are standalone systems. This could be due to higher development pressure and urban density in southern California, where most systems are retrofitted to existing developments.
- Most biofilters in southern California infiltrate to the groundwater exclusively (e.g., Sidebar 2). In southeast Australia, many systems collect outflow via an underdrain as well as infiltrate (e.g., Sidebar 1).
- Varying types of filter media tends to be layered and contain transition zones in southeast Australia (e.g., Sidebar 1). Very little information was available on filter media in southern California, but the Stormwater Best Management Practice Design and Maintenance Manual for Publicly Maintained Storm Drain Systems provide desired particle size distribution for filter media.

CONCLUSIONS

Biofiltration is a promising approach to managing stormwater runoff in urban areas with temperate and Mediterranean climates. While this technology is implemented on a large scale in southeast Australia, southern California is still in the early stages of constructing a system of biofilters as a BMP to control urban runoff. There are notable differences in biofilter design between southeast Australia and southern California, most notably the larger average size of southern California biofilters and higher diversity of drainage type in southeast Australia biofilters. The most striking difference with regards to stormwater management in these two locations is the greater seasonality of rainfall in southern California, with extended dry periods between rain events, even in the wet season. This climatological difference undoubtedly affects the function of biofilters in the Mediterranean climate of southern California. More research is needed to optimize biofilter design in this climate. One interesting design aspect worth investigation is the treatment of greywater using biofilters. Greywater can supply a continuous flow of water to maintain submerged zones during dry periods, potentially maintaining plant life and an anaerobic zone for denitrification.

The benefits of biofilters are rarely seen at the watershed level with the exception of projects like Little Stringybark Creek in Mt. Evelyn, VIC, where the strategic implementation of infiltrating biofilters and rainwater harvest tanks at the watershed scale have worked towards restoring the pre-development flow regime[2]. Due to the importation of water from northern California and the Colorado River to southern California, a pre-development flow regime in southern California watersheds may not be possible, especially in highly urbanized areas with high impervious cover. Nonetheless, southern California biofilters with underdrains and saturated zones used to harvest and treat stormwater runoff could substantially reduce storm flows and improve water quality in receiving waters. Biofilters, along with other low impact development strategies, can be used to improve and extend the life of existing stormwater management infrastructure.

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Figure captions

Figure 1. Mean monthly temperatures for Melbourne and Los Angeles. Data for 1994-2013: Melbourne[55] and Los Angeles[56].

Figure 2. Precipitation patterns for Melbourne and Los Angeles. Data for 1994-2013: Melbourne[55] and Los Angeles[56].

Figure 3. Distribution of antecedent dry days for Melbourne and Los Angeles. Inset: Distributions of antecedent dry days for Melbourne and Los Angeles during Driest and Wettest Years. Data for 1994-2013: Melbourne[55] and Los Angeles[56].

Figure 4. Examples of typical stormwater biofilter settings. (a) Curb cutout biofilter located in Culver City, CA, US on Baldwin Avenue; and (b) standalone biofilter located in Mt. Evelyn, VIC, AU in Morrison Reserve.

Tables

Table 1. Typical concentrations of constituents in stormwater runoff in southern California and southeast Australia.

Constituent	Unit	Southern California*	Southeast Australia**
Total Suspended Solids	mg/L	30 - 70	40 - 150
Total Nitrogen	mg/L	2 - 10	1 - 3
Total Phosphorus	mg/L	0.2 - 0.9	0.1 - 0.4
Cadmium	µg/L	2 - 5	4 - 5
Copper	µg/L	8 - 100	10 - 60
Lead	µg/L	2 - 30	10 - 140
Zinc	µg/L	80 - 500	100 - 300
E. coli	MPN/100mL	360 - 1,800	600 - 31,000

*Data from [57-60]. **Data from [5, 9, 61, 62].

Table 2. Characteristics of biofilters in Victoria and southern California. Where biofilter size varied within a site, averages were calculated based on the smallest size. Biofilter systems were identified and described using information gathered from Internet keyword searches for terms "rain garden," "biofilter," "stormwater biofilter," "stormwater biofiltration," and "stormwater LID" preceded by locations of interest (Los Angeles, Culver City, Irvine, San Diego, Orange County, or Melbourne). Additionally, websites of local watershed protection agencies and personal communication with agency personnel were used to determine site locations. The selected sites do not represent a random sample of all existing biofilters in each region, but biofilters were not selected to represent any particular characteristic(s), except that Victoria biofilters were selected to represent a range of ages.

Site Name	Age (yrs)	Size (m^2)	Catchment (ha)	Catchment Ratio	Catchment Land Use	Drainage Type	Setting
Southern California							
Elmer Avenue (Multiple)	4	12 – 24	16	-	res	Infiltration	Curb cutout
Riverdale Avenue	4	12 – 20	5.7	-	res	Infiltration/Underdrain	Curb cutout
Oros Street	7	12 – 20	2.0	-	res	Infiltration/Underdrain	Curb cutout
Bicknell Avenue (Multiple)	5	12 – 20	not avail.	-	res	Infiltration	Curb cutout
Baldwin Avenue (Multiple)	2	120	2.2	0.5%	res	Infiltration	Curb cutout
Ballona Creek East	3	1,900	5	3.8%	ind/comm	Infiltration	Standalone
Ballona Creek West	3	810	5	1.6%	res	Infiltration	Standalone
Hope Street	4	10-15	not avail.	-	comm	Infiltration	Curb cutout
Woodman Ave (multiple)	0.5	2,500	51	0.5%	res/comm	Infiltration	Curb cutout
Chatsworth Station (multiple)	2	Varies	15	-	comm	Underdrain	Parking Lot
LA Zoo Parking Lot (multiple)	3	1,400	5.5	2.5%	ind/comm	Infiltration	Parking Lot
Irvine- CalTrans	9	810	1.6	5.0%	comm	Underdrain	Standalone
Scripps Institution of Oceanography	4	150	0.7	2.3%	comm	Infiltration/Underdrain	Standalone
Average	**4**	**646**	**10**	**2.3%**			
Victoria							
Hereford Rd	4	100	0.9	1.1%	res	Infiltration/Underdrain	Standalone
Spring Street	2	14	0.1	1.3%	res	Infiltration/Underdrain	Standalone
Stringybark Blvd South	3	70	0.4	1.5%	res	Infiltration/Underdrain	Standalone
Fernhill Rd (multiple)	1	5-15	Varies	-	res	Infiltration	Curb cutout
Morrison Reserve	1	500	16	0.3%	res	Infiltration	Standalone

Otter St (multiple)	6	105	1	0.9%	res	Infiltration/Underdrain	Curb cutout
Napier and Kerr (multiple)	7	24	0.4	0.6%	res	Infiltration	Curb cutout
Cremorne St (multiple)	9	85	0.1	6.4%	ind/comm	Infiltration/Underdrain	Curb cutout
Parker St (multiple)	9	33	0.1	4.7%	res	Infiltration/Underdrain	Curb cutout
Avoca Crescent (multiple)	9	13	0.1	2.5%	res	Infiltration/Underdrain	Curb cutout
Clifton Hill (multiple)	6	200	3	0.7%	res	Underdrain	Standalone
Alleyne Ave (multiple)	8	76	0.1	15%	res	Infiltration	Curb cutout
Edinburgh Gardens	3	700	60	0.1%	res	Underdrain	Standalone
Average	**5**	**160**	**7**	**2.9%**			

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