Low Impact Development for Stormwater Management on the University of California, Berkeley Campus

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ABSTRACT

Excessive urban runoff poses a threat to society and the environment. Low impact development (LID) seeks to mitigate these threats by restoring pre-development hydrological conditions, such as runoff volume, to a site. LID practices have been implemented on the University of California, Berkeley (UCB) campus, but their effectiveness has not been evaluated. This study investigates the performance, cost-effectiveness, and optimal location for LID projects and practices on the UCB campus. To quantify performance, I compared runoff volume at LID project sites to a baseline scenario in which LID was not implemented. To determine cost-effectiveness, I tracked the cost of abating 1 m^3 of runoff over a 20-year period based on runoff volume abatement and project cost. To identify locations for future LID projects, I located areas on the UCB campus with steeper slopes and greater impervious surface coverage. The most effective LID projects on the UCB campus were those at Wellman Courtyard Parking (609.5 m^3 runoff abated/yr) and Dwinelle Lot (558.9 m^3 runoff abated/yr). The most effective LID practices were permeable pavement (0.501 m^3 runoff abated/m^2 of treatment area/yr) and disconnections (0.242 m^3 runoff abated/m^2 of treatment area/yr). The most cost-effective LID practices were rainwater harvesting and disconnections. The northeast quadrant of the UCB campus was the steepest and the most in need of LID implementation. Future construction should aim to incorporate disconnections, permeable pavement, and rainwater harvesting when possible. One possibility for a future LID project is the installation of permeable pavement at Foothill Lot.

KEYWORDS

best management practices, green infrastructure, runoff abatement, cost-effectiveness, site selection

INTRODUCTION

Urban stormwater runoff poses a threat to the environment as well as humans. Impervious materials such as cement cover much of the surface in urban areas and prevent precipitation from soaking into the ground (United States Environmental Protection Agency 2003). These impervious surfaces funnel runoff to storm drains that empty into nearby bodies of water (United States Environmental Protection Agency 2003). Along the way, the runoff can pick up a variety of pollutants including heavy metals, petroleum-derived hydrocarbons, and animal waste (Tsihrintzis and Hamid 1997). These pollutants can severely degrade the quality of the receiving body of water and negatively impact local wildlife – for example, lead can stunt fish growth and automobile oil is toxic to aquatic organisms (Tsihrintzis and Hamid 1997). In addition, impervious surfaces cause runoff to flow faster than it would in pre-development conditions (Konrad 2016). This leads to increased bank erosion and more frequent flooding of urban areas, both of which threaten infrastructure and private property (Konrad 2016). Mirchi et al. (2018) found that damages claimed due to urban flooding in South Florida totaled at least $327.3 million over a 15-year period. Luckily, low impact development (LID) has emerged as a technique to help mitigate these threats.

LID aims to mimic natural hydrologic functions of a site such as stormwater runoff volume (Zahmatkesh et al. 2015). The demand for LID implementation is greatest at sites with high runoff or flood-generation potential which are characterized by high rainfall intensity, low hydraulic conductivity, high water storage capacity of soil, high imperviousness, and/or steep slopes (Kaykhosravi et al. 2019; Zhang and Chui 2018). LID practices include green roofs, permeable pavement, rainwater harvesting systems, disconnection of impervious areas, and rain gardens (also known as bioretention cells). Green roofs are engineered rooftop systems composed mostly of specialized soil and a vegetation layer. They can partially replace the vegetation that was destroyed during construction of the building and return water to the atmosphere through evapotranspiration (Rowe 2011). Interlocking pavers, one form of permeable pavement on the University of California, Berkeley (UCB) campus, are concrete paving blocks spaced such that stormwater can seep through the gaps between them and into the ground (Huang et al. 2012). Rainwater harvesting systems collect runoff from rooftops for reuse and generally consist of a catchment area, pipes, a filter, a storage tank, and an overflow unit (Mun and Han 2012). Disconnection refers to the routing of runoff from impervious areas onto pervious surfaces in order to increase infiltration (Wang et al. 2019). Rain gardens are another means to increase infiltration – runoff drains from nearby rooftops into shallow depressions planted with vegetation (Dunnett and Clayden 2007). Each of the LID practices described above has been implemented on the UCB campus.

The LID practices on the UCB campus aim to restore the natural ecology and function of nearby Strawberry Creek (Kush et al. 2014). One mechanism through which they can achieve this goal is reduction of stormwater runoff volume. This would lessen the influx of harmful urban pollutants into the creek, reduce erosion of the creek banks, and prevent small pebbles that provide habitat for fish from being washed away (Kush et al. 2014). Although numerous studies suggest that LID can significantly reduce runoff volume, the effectiveness of existing LID projects on the UCB campus has not been evaluated (Eckart et al. 2017; T. Pine, *personal communication*). This situation as well as increasingly stringent stormwater control laws in California merits a quantification of the current runoff reduction capacity of LID projects on the UCB campus, an exploration of how to maximize runoff reduction while minimizing associated costs, and the identification of sites on the UCB campus that would benefit most from LID implementation.

The aim of this study is to answer the central research question: how can the effectiveness of LID practices on the UCB campus be maximized? This will be accomplished by answering the following three sub-questions. First: to what extent do green roofs, permeable pavement, rainwater harvesting systems, disconnections, and rain gardens on the UCB campus reduce annual stormwater runoff volume? Second: what is the cost per m^3 of abated stormwater runoff for green roofs, permeable pavement, rainwater harvesting systems, disconnections, and rain gardens on the UCB campus? Third: what sites on the UCB campus have the greatest demand for LID implementation?

METHODS

Study sites

Each of the study sites was part of the UCB campus on the east side of San Francisco Bay. The San Francisco Bay area experiences a Mediterranean-type climate which is characterized by warm, dry summers and cool, wet winters. Annual precipitation is highly variable and can range from approximately 11 to 62 inches per year (Ackerly et al. 2018).

The first study site was the roof of Li Ka Shing Center (Figure 1). About 40 percent of the total roof area is dedicated to an extensive green roof that consists of small native succulents (Cockrell 2012). Most of these succulents have died and been replaced by weeds due to lack of proper maintenance (T. Pine, *personal communication*). The remaining 60 percent of the total roof area is cement and metal.

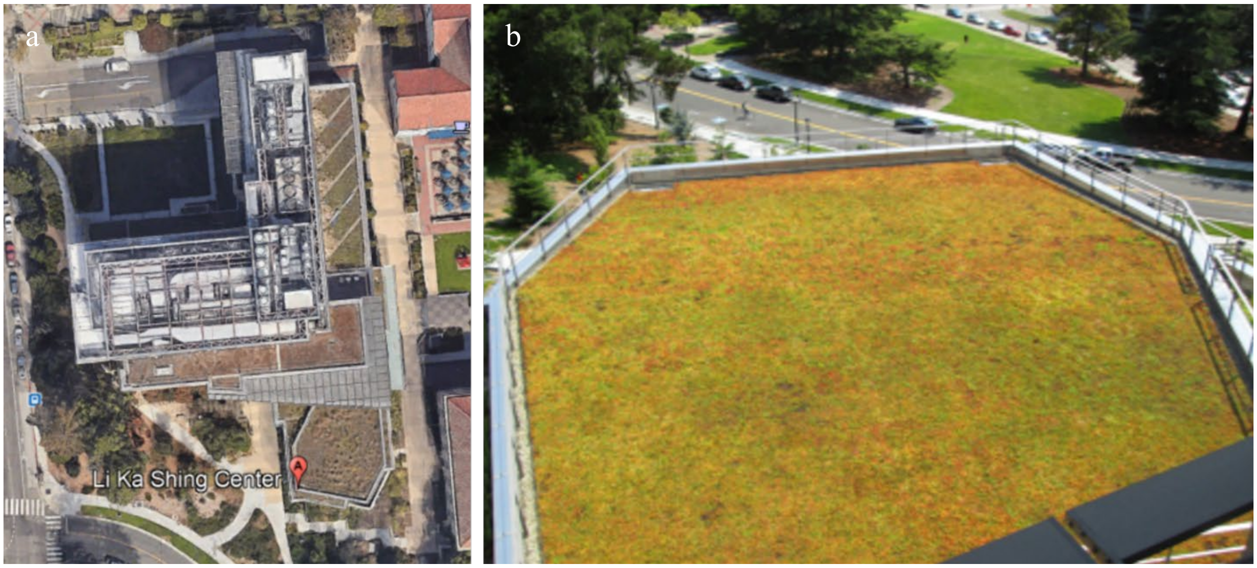

Figure 1. Li Ka Shing Center. Figure 1(a) is a satellite image of the Li Ka Shing Center roof. Figure 1(b) is a close-up photograph of a portion of the green roof.

The second study site was Wellman Courtyard Parking (Figure 2). It consists of interlocking pavers, a type of permeable pavement, that were installed in the mid-2000s (V. Wong, *personal communication*). These interlocking pavers lie over a thick gravel layer which provides space for runoff to collect before infiltrating into the ground.

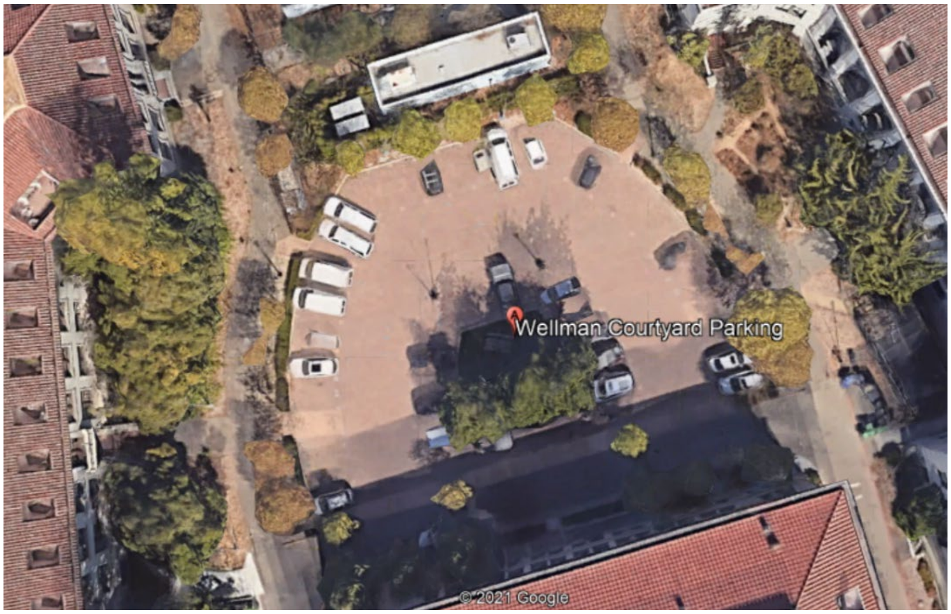

Figure 2. Satellite image of Wellman Courtyard Parking.

The third study site was part of the Hearst Field Annex (HFA) Building A and B rooftops (Figure 3). Approximately 6900 ft^2 of the metal Building A and B rooftops drain into downspouts that have been redirected into a 2300-gallon polyethylene rain tank. Water from the rain tank is used to water the 8208 ft^2 lawn at the center of HFA. The rainwater harvesting system was installed in 2018. A bioswale is currently being designed that will absorb overflow from the rain tank (D. Vilekar, *personal communication*).

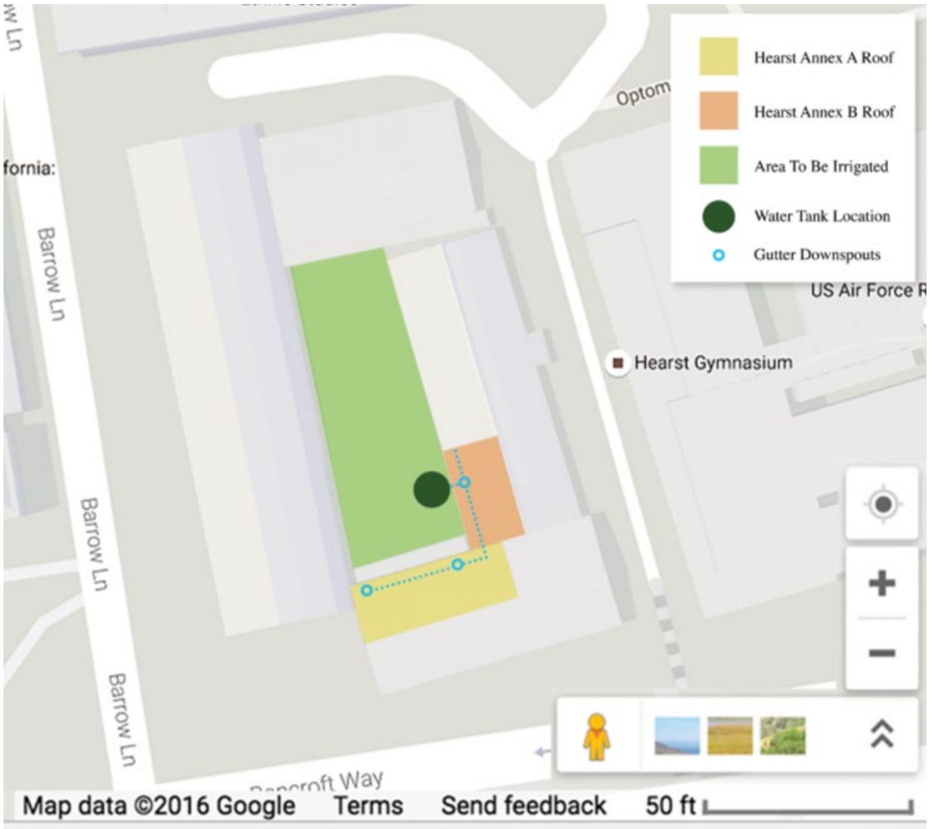

Figure 3. Diagram of Hearst Field Annex rainwater harvesting system. The study site (polygon outlined in the National Stormwater Calculator) is the orange and yellow area.

The fourth study site was Dwinelle Lot and the lawn and stormwater detention pond west of Dwinelle Lot and south of the Valley Life Sciences Building (Figure 4). Runoff from Dwinelle Lot is drained and piped to the lawn where much of the water is absorbed. Any excess water is drained and piped again to the stormwater detention pond which is planted with shrubs native to the San Francisco Bay area. Water in the pond percolates into the ground and any overflow drains into Strawberry Creek (Kush et al. 2014). For simplicity, this study site will be referred to as “the Dwinelle Lot disconnection”.

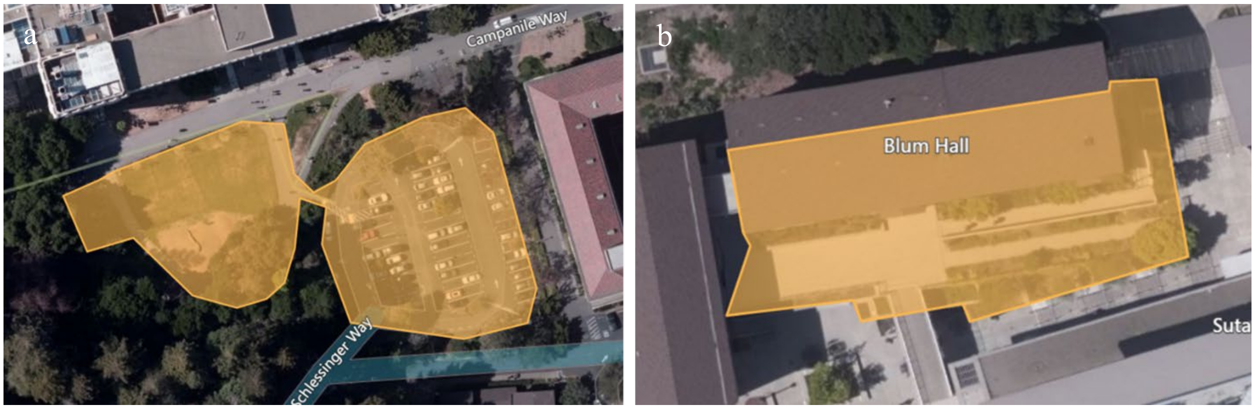

Figure 4. The yellow area is the National Stormwater Calculator polygon that encompasses the Dwinelle Lot disconnection and Blum Hall study sites. The polygon in Figure 4(a) encompasses Dwinelle Lot, the lawn onto which the disconnection drains, and the stormwater detention pond. The polygon in Figure 4(b) encompasses the southern half of the Blum Hall rooftop as well as the walkways and rain garden onto which it drains.

The final study site was the southern half of the Blum Hall roof and the walkways and rain garden that lie underneath (Figure 4). The rain garden is a series of catchments planted with native vegetation that are fully irrigated by runoff from the southern half of the Blum Hall roof. It has low maintenance costs because it does not require irrigation, fertilizer, or mowing (Kush et al. 2014).

Stormwater runoff abatement

To test the impact of LID projects on site hydrology, I used the National Stormwater Calculator because it is designed for hydrological analysis of sites less than 12 acres within the United States (United States Environmental Protection Agency 2019). The National Stormwater Calculator uses the EPA Storm Water Management Model as its computational engine and automatically imports soil, topography, rainfall, and evaporation data from several national databases when they are available for a site and surrounding areas.

The National Stormwater Calculator assumes that the area devoted to green roofs, permeable pavement, and rainwater harvesting systems comes from the site's impervious land cover while the area devoted to rain gardens and disconnections comes from the site's pervious land cover. This necessitated that I separate the study sites into two groups. Group 1 consisted of the Li Ka Shing Center roof, Wellman Courtyard Parking, and the HFA rainwater harvesting system. Group 2 consisted of the Dwinelle Lot disconnection and Blum Hall. I created a baseline scenario which represented site conditions had LID practices not been implemented. Because the area devoted to LID practices in Group 1 came from impervious land cover, this area was replaced with impervious surfaces in the baseline scenario for Group 1. For the same reason, the area devoted to LID practices in Group 2 was replaced with lawns in the baseline scenario in Group 2.

To find stormwater runoff abatement, I compared runoff under the baseline scenario to runoff under current conditions in which LID practices have been implemented (Table 1). First, I outlined the study site using the polygon drawing tool and recorded the total study site area. Because soil type data was available only for areas surrounding the UCB campus and not the campus itself, I assumed that each study site had the same soil type as the nearest location with available data. I made the same assumptions for soil drainage and topography, except in the case of the Li Ka Shing Center roof which I assumed was flat. For precipitation and evaporation data, I used the Oakland Museum weather station because it was the nearest weather station to the UCB campus. To describe the baseline scenario land cover, I outlined impervious surfaces (and the LID area for Group 1) at the study site and recorded the area. I divided this area by the total study site area to obtain the percentage of the study site covered by impervious surfaces. I assumed that the remaining portion of the study site was lawn. I ran the model across 20 years with an event threshold of 0 and without ignoring consecutive days of rainfall to improve the accuracy of rainfall and runoff estimates. I then recorded the baseline scenario average annual runoff.

Table 1. Description of baseline and current scenarios at each study site.

Study site	Baseline scenario	Current scenario
Li Ka Shing Center roof	100% impervious	38% of baseline impervious area is being treated by green roof
Wellman Courtyard Parking	94% impervious, 6% lawn	100% of baseline impervious area is being treated by permeable pavement
HFA rainwater harvesting system	100% impervious	100% of baseline impervious area is being treated by rainwater harvesting
Dwinelle Lot disconnection	65% impervious, 35% lawn	86% of baseline impervious area is being treated by disconnection
Blum Hall	65% impervious, 35% lawn	57% of baseline impervious area is being treated by rain garden

Next, I edited the land cover description to reflect the current implementation of LID practices. I calculated LID coverage in a manner analogous to baseline scenario land cover. Each LID practice required its own input parameters. I retained default values for the input parameters unless observation of the study site or documentation showed that these default values did not apply (Table 2). I ran the model again and recorded the current scenario average annual runoff.

Table 2. National Stormwater Calculator input parameters for LID practices at each study site.

Study site	LID practice	Input parameters
Li Ka Shing Center roof	Green roof	Default values
Wellman Courtyard Parking	Permeable pavement	Default values
HFA rainwater harvesting system	Rainwater harvesting system	Cistern size = 2300 gal, emptying rate = 94 gal/day, 0.14 tanks/1000 sq. ft.
Dwinelle Lot disconnection	Disconnection	Capture ratio = 63%
Blum Hall	Rain garden	Capture ratio = 88%

Finally, I subtracted the current runoff from baseline runoff to obtain stormwater runoff abated due to LID implementation in cm. To convert this number to m^3 of abated runoff, I multiplied abated stormwater runoff in m by the total study site area in m^2. I calculated the percent reduction in runoff using the percent change formula. To normalize abated runoff to treatment area, I divided m^3 of abated runoff for each study site by the area devoted to the LID practice at that site.

Cost per m^3 of abated runoff

To estimate capital costs for LID projects, I again used the National Stormwater Calculator. In addition to estimating runoff for a baseline and current scenario, the National Stormwater Calculator generates an upper and lower bound on capital costs for developing the baseline scenario into the current scenario. For each study site, I characterized the project type as re-development with poor site suitability due to the urban nature of the UCB campus. I chose San Francisco as the cost region because it was the closest available option. To supplement the National

Stormwater Calculator estimates, I gathered available records of project budgets from UCB Capital Strategies and the UCB chapter of Engineers for a Sustainable World.

To track the cost per m^3 of abated runoff over the course of the National Stormwater Calculator simulations, I applied Eq. 1 to a 20-year span. I used this equation on capital costs generated by the National Stormwater Calculator and on project budgets if they were available. *A* represents the cost of abating 1 m^3 of runoff after *N* years, *C* represents the cost of the LID project, and *R* represents the average annual abated runoff in m^3.

$$A = \frac{C}{N * R} \tag{1}$$

Sites with high LID demand

To identify the sites with the greatest demand for LID implementation, I used QGIS (QGIS Development Team 2021). I used impervious surfaces and steeper slopes as criteria for sites with greater runoff generation potential because rainfall intensity was relatively constant across the UCB campus and datasets for hydraulic conductivity and water storage capacity of soil were not available.

First, I applied the Slope tool to a 1/3 arc-second digital elevation model of the UCB campus area to generate a map of slope. I manually changed the intervals for slope to approximately correspond to the intervals provided by the National Stormwater Calculator – 0 to 2 percent, 2 to 5 percent, 5 to 10 percent, 10 to 15 percent, and 15 percent or greater. Next, I overlaid the UCB property boundary and impervious surfaces (buildings, roads, and parking lots) on the slope layer. After reprojecting all layers to NAD83 / California zone 3 (ftUS), I clipped them to the UCB property boundary.

RESULTS

Stormwater runoff abatement

The green roof on Li Ka Shing Center modestly decreased runoff. The National Stormwater Calculator estimated that all study sites experience an average of 58.22 cm of rainfall annually. In the baseline scenario, the Li Ka Shing Center roof generated 49.86 cm of runoff annually, corresponding to a volume of 1755.46 m^3 (Table 3; Figure 5). In the current scenario, the roof generated 46.36 cm of runoff annually, corresponding to a volume of 1632.05 m^3. There was a 3.5 cm decrease in runoff amount and a 123.41 m^3 decrease in runoff volume between baseline and current scenarios. This represented a 7% decrease in runoff due to the installation of a green roof.

Table 3. National Stormwater Calculator estimates of runoff in baseline and current scenarios.

Study site	Baseline runoff volume (m^3)	Current runoff volume (m^3)	Runoff abated due to LID (m^3)	Percent difference
Li Ka Shing Center roof	1755.46	1632.05	123.41	7%
Wellman Courtyard Parking	612.46	2.96	609.5	99.5%
HFA rainwater harvesting system	323.81	254.6	69.22	21%
Dwinelle Lot disconnection	1403.86	844.96	558.9	40%
Blum Hall	108.37	44.92	63.45	59%

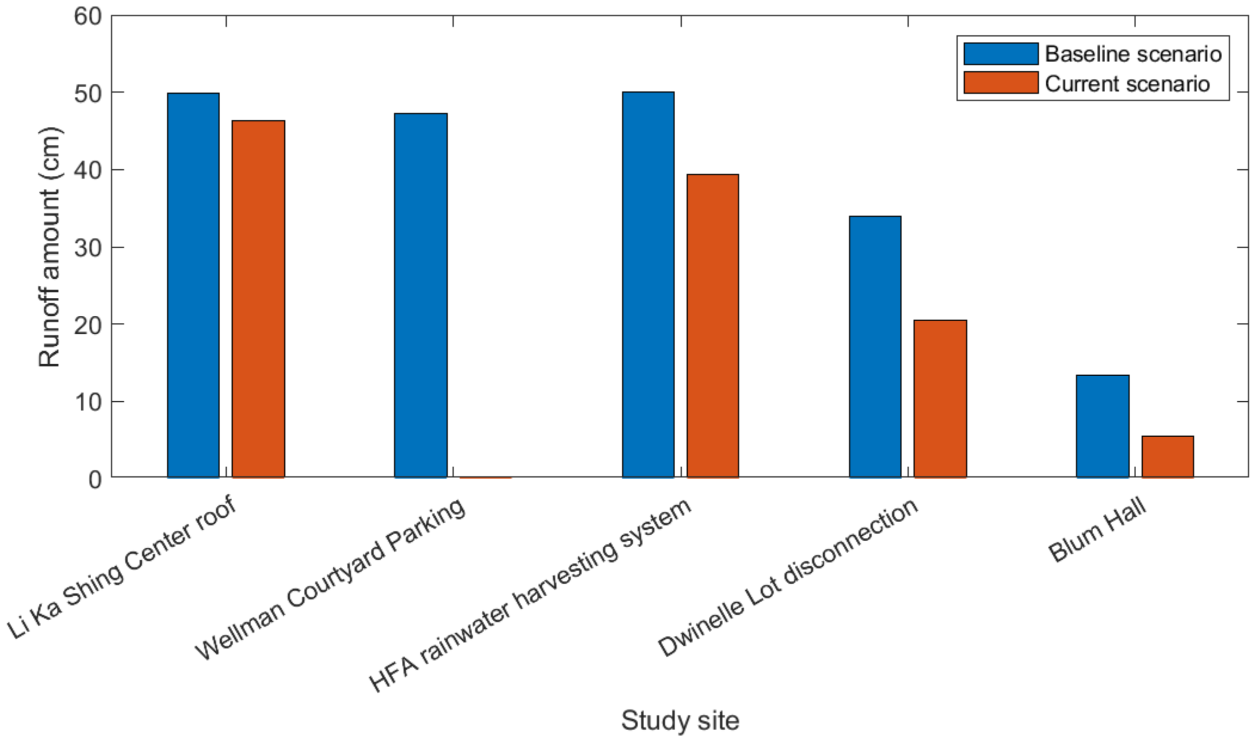

Figure 5. Comparison of National Stormwater Calculator estimates of baseline and current scenario runoff amount at each study site.

The interlocking pavers in Wellman Courtyard Parking almost completely eliminated site runoff. In the baseline scenario, Wellman Courtyard Parking generated 47.29 cm of runoff annually, corresponding to a volume of 612.46 m^3 (Table 3; Figure 5). In the current scenario, the parking lot generated 0.23 cm of runoff annually, corresponding to a volume of 2.96 m^3. There was a 47.06 cm decrease in runoff amount and a 609.5 m^3 decrease in runoff volume between baseline and current scenarios. This represented a 99.5% decrease in runoff due to the installation of interlocking pavers.

The rainwater harvesting system at HFA was somewhat effective in reducing runoff. In the baseline scenario, the HFA study site generated 50.01 cm of runoff annually, corresponding to a volume of 323.81 m^3 (Table 3; Figure 5). In the current scenario, the site generated 39.32 cm of runoff annually, corresponding to a volume of 254.6 m^3. There was a 10.69 cm decrease in runoff amount and a 69.22 m^3 decrease in runoff volume between baseline and current scenarios. This represented a 21% decrease in runoff due to the installation of the rainwater harvesting system.

The Dwinelle Lot disconnection was effective in reducing runoff. In the baseline scenario, the study site generated 34.01 cm of runoff annually, corresponding to a volume of 1403.86 m^3

(Table 3; Figure 5). In the current scenario, the site generated 20.47 cm of runoff annually, corresponding to a volume of 844.96 m^3. There was a 13.54 cm decrease in runoff amount and a 558.9 m^3 decrease in runoff volume between baseline and current scenarios. This represented a 40% decrease in runoff due to the installation of the disconnection and detention pond.

The Blum Hall rain garden was very effective in reducing runoff. In the baseline scenario, the study site generated 13.39 cm of runoff annually, corresponding to a volume of 108.37 m^3 (Table 3; Figure 5). In the current scenario, the site generated 5.55 cm of runoff annually, corresponding to a volume of 44.92 m^3. There was a 7.84 cm decrease in runoff amount and a 63.45 m^3 decrease in runoff volume between baseline and current scenarios. This represented a 59% decrease in runoff due to the installation of the rain garden.

After normalizing the abated runoff volume to LID area, I found that the effectiveness of LID practices within Group 1 and Group 2 varied significantly. Permeable pavement was the most effective LID practice in Group 1 at 0.501 m^3 of runoff abated per m^2 of LID area, distantly followed by rainwater harvesting systems at 0.107 m^3 of runoff abated per m^2 of LID treatment area (Table 4). Green roofs were the least effective LID practice in Group 1 at 0.0922 m^3 of runoff abated per m^2 of LID treatment area. In Group 2, disconnections were more effective than rain gardens. Disconnections and rain gardens abated 0.242 and 0.212 m^3 of runoff per m^2 of LID treatment area, respectively.

Table 4. Volume of abated runoff normalized to LID treatment area.

LID practice	m^3 runoff abated per m^2 of treatment area
Green roof	0.0922
Permeable pavement	0.501
Rainwater harvesting system	0.107
Disconnection	0.242
Rain garden	0.212

Cost per m^3 of abated runoff

Capital costs of the Li Ka Shing Center green roof ranged from $236,170.51 to $318,399.38 according to the National Stormwater Calculator. UCB Capital Strategies had no record of estimated cost. Based on the National Stormwater Calculator estimate, the cost per m^3 of abated runoff ranged from \$1,913.70 to \$2,580.00 one year after installation of the green roof (Table 5; Figure 6). After 20 years, the cost per m^3 of abated runoff fell between \$95.70 and \$129.00.

Table 5. Cost (in USD) per m^3 of runoff abated due to LID implementation at each study site. No asterisk indicates that costs are based on National Stormwater Calculator estimates. Asterisks indicate that costs are based on records of project budgets.

Study site	Years after LID implementation				
	1	**5**	**10**	**15**	**20**
Li Ka Shing Center roof	2247.00	449.35	224.70	149.80	112.35
Wellman Courtyard Parking	373.35	74.67	36.34	24.89	18.67
Dwinelle Lot disconnection	4.92	0.99	0.49	0.33	0.25
Blum Hall	1072.80	214.55	107.30	71.55	53.60
Wellman Courtyard Parking*	564.00	112.80	56.40	37.60	28.20
HFA rainwater harvesting system*	304.02	60.80	30.40	20.27	15.20

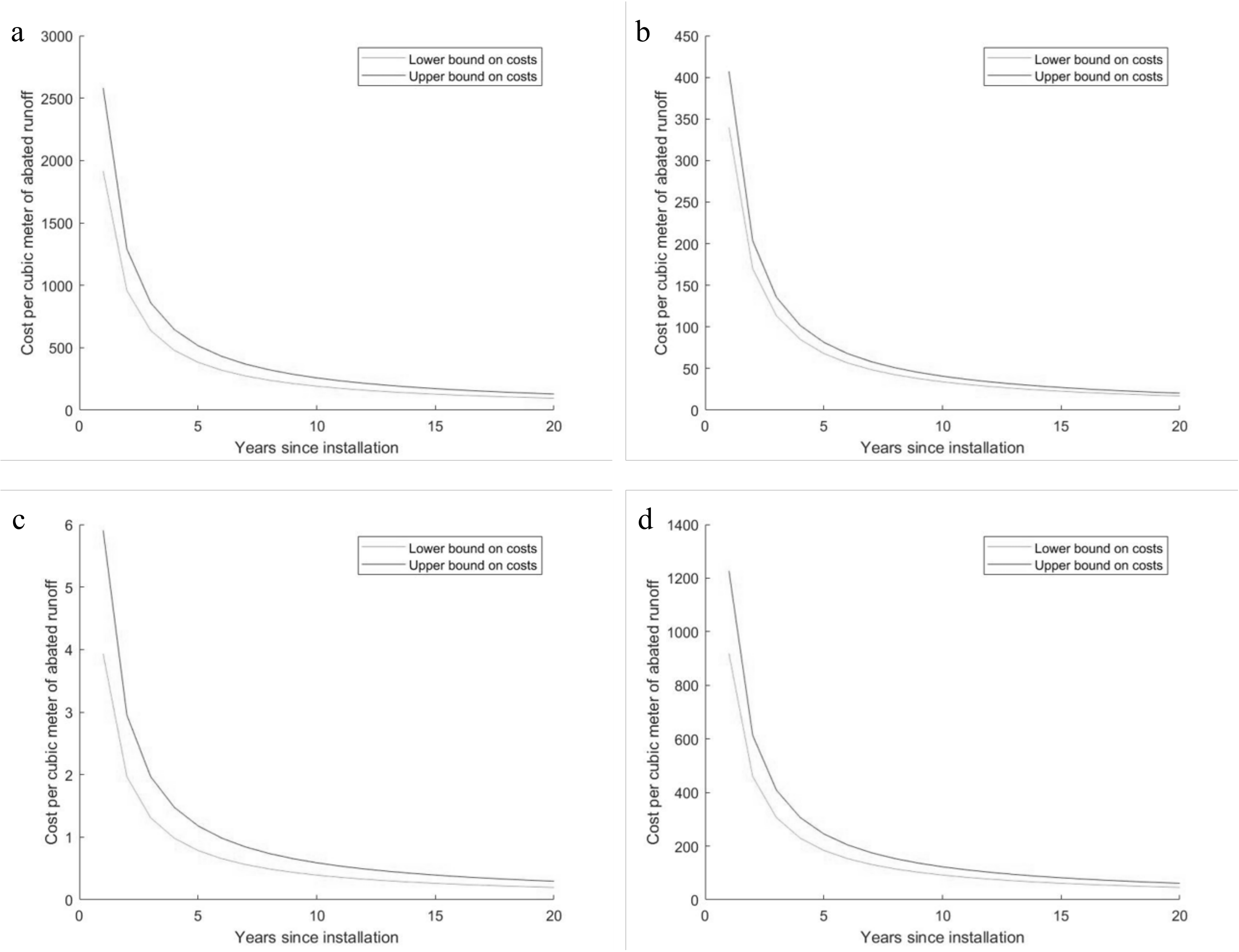

Figure 6. Cost (in USD) per m^3 of abated runoff over a 20-year period based on National Stormwater Calculator estimates of capital costs. Figure 6(a) is the Li Ka Shing Center roof. Figure 6(b) is Wellman Courtyard Parking. Figure 6(c) is the Dwinelle Lot disconnection. Figure 6(d) is Blum Hall.

Capital costs of pervious pavement installation in Wellman Courtyard Parking ranged from \$207,033.73 to \$248,040.54 according to the National Stormwater Calculator. The records I obtained from Berkeley Capital Strategies showed that there were two design schemes for Wellman Courtyard Parking and three bids for construction but did not indicate which scheme or bid was selected. Scheme A for Wellman Courtyard Parking had a projected construction cost of \$410,680 and projected total of \$574,952. Scheme B had a projected construction cost of \$408,040 and projected total of \$571,256. After I subtracted costs unrelated to the installation of the pervious pavement, the Scheme A total was \$345,316 and the Scheme B total was \$342,148. The lump sum base bids by contractors ranged from \$428,000 to \$488,350. Based on the National Stormwater Calculator estimate, the cost per m^3 of abated runoff ranged from \$339.68 to \$406.96 one year after installation and from \$16.98 to \$20.35 twenty years after installation (Table 5; Figure 6). Based on my adjusted Scheme A and Scheme B total cost, the cost per m^3 of abated runoff ranged from \$561.36 to \$566.56 one year after installation and from \$28.07 to \$28.33 twenty years after installation (Table 5; Figure 7).

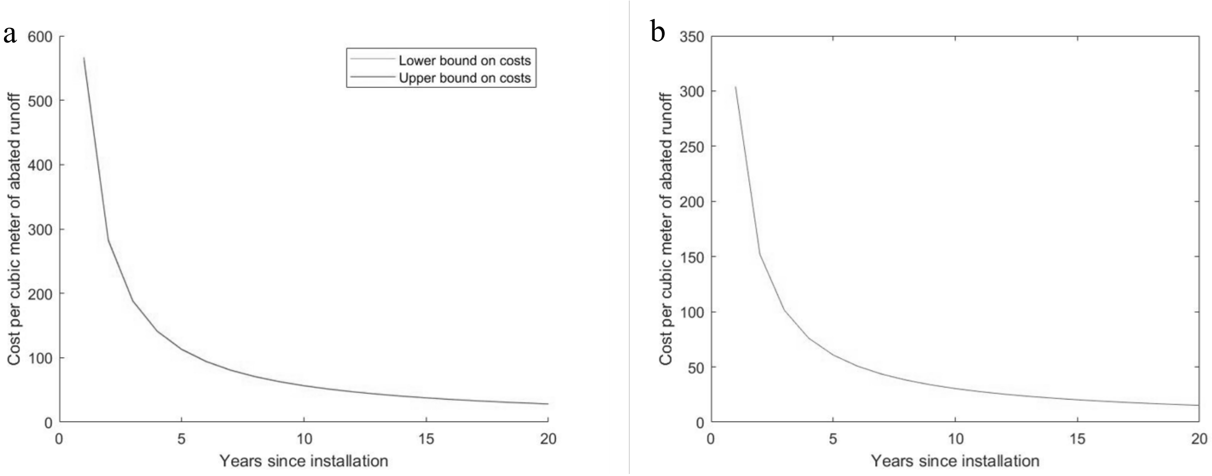

Figure 7. Cost (in USD) per m^3 of abated runoff over a 20-year period based on project budget records. Figure 7(a) is based on the adjusted budgets for two design schemes for Wellman Courtyard Parking. The lower and upper bounds on cost are very close together and appear as one line on the graph. Figure 7(b) is based on an adjusted project budget for the HFA rainwater harvesting system. Because there was only one budget for the HFA rainwater harvesting system, there is not a lower and upper bound on cost.

The National Stormwater Calculator failed to generate an estimate of capital costs for the HFA rainwater harvesting system. The records I obtained from Engineers for a Sustainable World showed that the combined project budget for the rainwater harvesting system and bioswale was \$23,044. After I subtracted the cost of required bioswale materials, the cost of the rainwater harvesting system totaled \$21,044. Based on this estimate, the cost per m^3 of abated runoff was \$304.02 one year after installation and \$15.20 twenty years after installation (Table 5; Figure 7).

Capital costs of the Dwinelle Lot disconnection ranged from \$2,196.65 to \$3,299.66 according to the National Stormwater Calculator. UCB Capital Strategies had no record of estimated cost. Based on the National Stormwater Calculator estimate, the cost per m^3 of abated runoff ranged from \$3.93 to \$5.90 one year after implementation of the disconnection and detention pond (Table 5; Figure 6). After 20 years, the cost per m^3 of abated runoff fell between \$0.20 and \$0.30.

Capital costs of the Blum Hall rain garden ranged from \$58,307.52 to \$77,830.76 according to the National Stormwater Calculator. UCB Capital Strategies had no record of estimated cost. Based on the National Stormwater Calculator estimate, the cost per m^3 of abated runoff ranged from \$919 to \$1,226.60 one year after installation of the rain garden (Table 5; Figure 6). After 20 years, the cost per m^3 of abated runoff fell between \$45.90 and \$61.30.

The cost effectiveness of different LID practices within Group 1 and Group 2 varied to a great extent. Rainwater harvesting systems were the most cost-effective LID practice in Group 1 by a small margin. Based on project budget data, it was \$259.98 cheaper to abate 1 m^3 of runoff through rainwater harvesting systems than through the next most cost-effective option, permeable pavement, after one year and \$13 cheaper after 20 years. Based on National Stormwater Calculator cost estimates, abating 1 m^3 of runoff through permeable pavement was \$1873.65 cheaper after 1 year and \$93.68 cheaper after 20 years than abating it through green roofs, the least cost-effective option in Group 1. In Group 2, disconnections were the more cost-effective LID practice by a margin of \$1067.88 after one year and \$53.35 after 20 years per m^3 of runoff abated.

Sites with high LID demand

Because the UCB property boundary included a large area of the Berkeley hills that is not part of the main campus, I defined the UCB campus to be only areas west of the line connecting Cyclotron Road and Witter Rugby Field. I found that the UCB campus is relatively flat with moderate variation in slope. The southwest quadrant of campus was the flattest region of campus with the least variation in slope – nearly the entire quadrant had a slope less than 2 percent (Figure 8). Although the majority of the northwest and southeast quadrants of campus also had a slope less than 2 percent, a greater proportion of the area in these two quadrants reached 2 to 5 percent slope. Small sites near University House and Haviland Hall in the northwest quadrant and near Memorial Stadium in the southeast quadrant reached 5 to 10 percent slope. The northeast quadrant of campus had the greatest proportion of area with slope over 2 percent, most of which fell between 2 and 5 percent slope and was located between Gayley Road and Cyclotron Road. Within the northeast quadrant of campus, slope increased to the east. Most of the area surrounding Foothill Lot was between 5 and 10 percent slope with some areas reaching 10 to 15 percent slope.

Figure 8. Map of the UCB campus showing slope and impervious surfaces. Green areas indicate low runoff generation and magenta areas indicate high runoff generation.

Much of the surface area of the UCB campus was covered by impervious surfaces and especially by buildings (Figure 9). Impervious surfaces were relatively evenly dispersed across the UCB campus, although the northwest quadrant had slightly more pervious surface than the other three quadrants. Because it had the steepest slopes and the distribution of impervious surfaces across the UCB campus was relatively homogenous, I identified the northeast quadrant of the UCB campus as the area with the greatest runoff generation and therefore, the greatest demand for LID implementation.

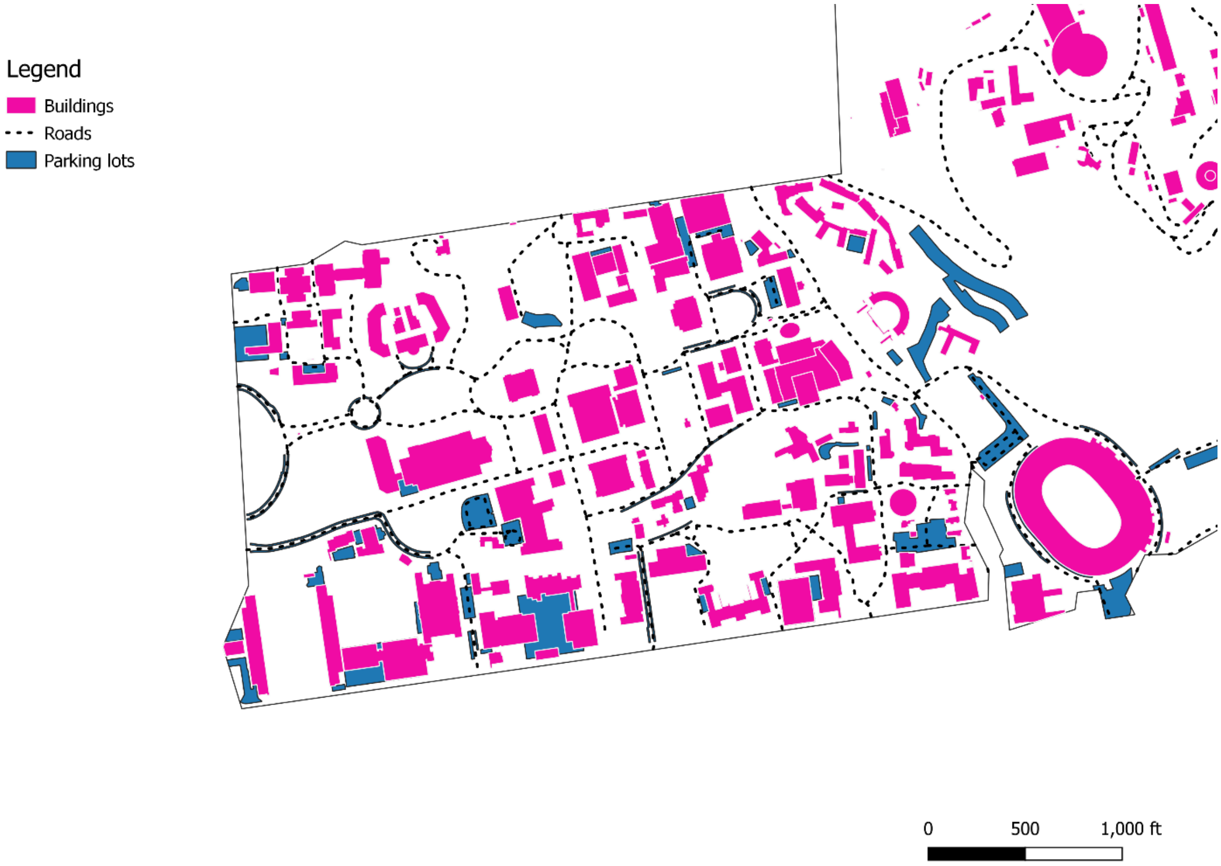

Figure 9. Map of the UCB campus showing impervious surfaces. Buildings are shown in magenta, roads are represented with black dotted lines, and parking lots are shown in blue.

DISCUSSION

Knowledge of the most effective existing LID projects, the most effective and cost-effective LID practices, and the sites with the greatest demand for LID provides the groundwork for a plan to maximize the effectiveness of LID on the UCB campus. Based on runoff volume reduction, the most effective LID projects were those at Wellman Courtyard Parking and Dwinelle Lot. The most effective LID practices were permeable pavement and disconnections and, taking into account the costs associated with installation, the most cost-effective LID practices were rainwater harvesting systems and disconnections. Although numerical results associated with performance and cost can vary widely depending on a number of factors, my results and those of similar studies suggest that certain LID practices are generally more effective and/or less costly than others. Because the northeast quadrant of the UCB campus had the steepest slopes, it generated the most runoff and would benefit most from LID implementation.

Stormwater runoff abatement

Because the vast majority of the total runoff volume reduction associated with LID implementation was due to the projects at Wellman Courtyard Parking and Dwinelle Lot, these were the most important LID projects among those studied. It is rational to assume that an LID project which abates an outsized proportion of UCB campus runoff also has increased importance in maintaining the health of Strawberry Creek, given that many studies have linked increased urban runoff with negative outcomes for stream health (Fletcher et al. 2014; Ladson et al. 2007; Finkenbine et al. 2000). In Group 1, the permeable pavement at Wellman Courtyard Parking abated approximately five times as much runoff as the green roof at Li Ka Shing Center and over eight times as much as the rainwater harvesting system at Hearst Field Annex. In Group 2, the disconnection at Dwinelle Lot abated almost nine times as much runoff as the rain garden at Blum Hall. These results are reasonable given that runoff volume reduction is a function of both the area treated by LID and the effectiveness of the LID practice. Differences in area treated by LID can explain the disparity in runoff abatement between the Dwinelle Lot disconnection and the Blum Hall rain garden – the area treated by rain garden was only 13% of the area treated by disconnection. Differences in the effectiveness of LID practices can explain the disparity in runoff abatement between Wellman Courtyard Parking and the Li Ka Shing Center roof despite the similar area treated by LID at both study sites.

To maximize runoff abatement over a given area, future LID projects on the UCB campus should incorporate permeable pavement and disconnections because these were the two most effective LID practices in Groups 1 and 2, respectively. In Group 1, permeable pavement was approximately five times more effective than green roofs and rainwater harvesting systems at abating runoff. Though sparse research has directly compared LID practices on the basis of effectiveness, these findings have some support in the existing literature. Bean et al. (2007) found that permeable pavement could completely eliminate the generation of runoff, even in the most intense rainfall events. Meanwhile, Carter and Rasmussen (2005) identified a negative relationship between the amount of rainfall and the percent of rainfall that a green roof can retain, and the effectiveness of rainwater harvesting systems is highly dependent on the magnitude of rainfall events (Freni and Liuzzo 2019). In Group 2, disconnections were about 14 percent more effective than rain gardens. The effectiveness of disconnections is supported by Ellis and Viavattene (2014), who found that a disconnection-infiltration basin system similar to the one at Dwinelle Lot could reduce runoff from a 30-year storm by 95%.

Conclusions drawn from runoff reduction normalized to LID treatment area rest on the simplifying assumption that the relationship between runoff reduction and LID treatment area is the same for all LID practices. Chui et al. (2016) found that the relationship between runoff reduction and green roof area is linear, but there is no evidence this is true for other LID practices. Furthermore, site selection and project design can have a major influence on LID project performance. This is demonstrated in a number of studies such as Zhang et al. (2000), in which some green roofs on the Beijing Normal University campus nearly completely eliminated runoff while others had hardly any impact at all. Therefore, the volume of runoff abated per m^2 of LID treatment area derived from specific LID projects on the UCB campus is not a number that applies universally.

Cost per m^3 of abated runoff

To minimize costs associated with reducing runoff, future LID projects on the UCB campus should incorporate rainwater harvesting systems and disconnections because these were the two most cost-effective LID practices in Groups 1 and 2, respectively. Regardless of whether cost-effectiveness was calculated based on budget records or National Stormwater Calculator estimates, the HFA rainwater harvesting system was more cost-effective than the permeable pavement at Wellman Courtyard Parking, and the green roof at Li Ka Shing Center was by far the least cost-effective in Group 1. This ranking of cost effectiveness is supported by Joksimovic and Alam (2014), who found that the rainwater harvesting was more cost-effective than permeable pavement and that permeable pavement was more cost-effective than green roofs. Chui et al. (2016) identified the same trend in cost-effectiveness, although cost-effectiveness was calculated in terms of peak flow reduction rather than runoff volume reduction. In Group 2, it was approximately 200 times cheaper to abate 1 m^3 of runoff through the disconnection at Dwinelle Lot than through the rain garden at Blum Hall. Although the differences in baseline scenarios between Group 1 and Group 2 prevent an “apples-to-apples” comparison, the cost per m^3 of abated runoff for disconnections was so much lower than any other LID practice in either group that it seems reasonable to conclude that they are generally the most cost-effective LID practice. It is not difficult to see why this is the case when comparing costs associated with disconnection to those associated with, for example, rainwater harvesting systems, the most cost-effective LID practice in Group 1. Material costs of the Dwinelle Lot disconnection were related to replumbing the storm drain to carry runoff from the parking lot to the lawn and installing piping to carry runoff from the lawn to the stormwater detention pond (Kush et al. 2014). Meanwhile, in addition to the $2000 required for piping, the HFA rainwater harvesting system required the purchase and installation of 11 other items that cost over $11,000 collectively including a pump, float switch, rain pump controller, back flow preventer, and the rain tank itself.

It should be noted that cost-effectiveness was determined in terms of capital costs and runoff abatement. Because the life-cycle maintenance costs for individual LID practices are not well-documented, they were not accounted for in this study. However, these maintenance costs are not always negligible. For instance, rainwater harvesting systems require regular roof washing, inflow filter cleaning, and tank disinfection that can total about $1,000 per year (Houdeshel et al. 2011). Also, runoff abatement may not be the only environmental benefit of an LID practice. Green roofs serve several other purposes including urban heat island effect mitigation and air pollutant reduction (Eckhart et al. 2017). If any of these benefits are a significant factor in selecting which LID practice to implement, a ranking of cost-effectiveness based on runoff abatement performance will be of limited use. Finally, because site selection and project design influence project performance which in turn influences cost-effectiveness, the cost per m^3 of abated runoff derived from specific LID projects on the UCB campus is not a universally generalizable number.

Sites with high LID demand

Based on slope and imperviousness, the northeast quadrant of the UCB campus should be prioritized when siting future LID projects because it had the greatest runoff generation potential and thus, the greatest demand for runoff reduction. There are two important caveats to this conclusion. First, in addition to slope and imperviousness, other variables such as soil permeability, depth to the groundwater table, and depth to the first restrictive layer can influence runoff generation (Kaykhosravi et al. 2019). The impact these variables have on runoff generation across quadrants of the UCB campus is unknown as data on these variables could not be found. Second, high demand for LID does not imply that LID implementation is feasible. Some characteristics that increase demand for LID actually decrease feasibility, such as the presence of impermeable soils (Eckart et al. 2017). Therefore, although the demand for LID in the northeast quadrant is high, it may be prohibitively difficult or costly to implement LID practices in certain locations.

Limitations and future directions

Although its use was necessitated by time constraints and a lack of technical expertise, the National Stormwater Calculator is a planning level tool – better estimates of runoff abatement may have been obtained by using a more customizable model, such as the EPA Storm Water Management Model, and better estimates of costs may have been obtained by consulting with local contractors who specialize in LID construction. In addition, as mentioned earlier, the heavy influence of site selection and project design prevent the numerical results for runoff abatement and cost-effectiveness of LID practices from being universally applicable. However, the rankings of LID practices in terms of runoff abatement and cost-effectiveness are more generalizable because the difference between the numerical results associated with each LID practice was very large in most cases. Furthermore, the ranking for cost-effectiveness was supported by the results of similar studies (Joksimovic and Alam 2014; Chui et al. 2016).

There are many opportunities for future research on LID practices given the wide range of factors such as soil conditions and vegetation choices that influence LID performance and cost (Ahiablame et al. 2012). A better understanding of the relationship between any of these factors and performance and cost would provide guidance for maximizing LID performance given a specified budget and multiple options for project sites. In addition, it is likely that California will suffer from increased precipitation volatility in the 21st century as a result of climate change, meaning that long periods of severe drought will likely be followed by long periods of extreme wetness (Swain et al. 2018). The ability of LID practices to reduce runoff quantity and slow peak flow merits further research on their potential to mitigate increased runoff during these extreme precipitation events.

Conclusions

One way to address the problems associated with urban stormwater runoff on the UCB campus is to maximize the effectiveness of LID. This entails the preservation of the most effective existing projects as well as construction of new projects that maximize runoff abatement and minimize cost. The LID projects at Wellman Courtyard Parking and Dwinelle Lot should not be disturbed as they currently play the largest roles in abating campus runoff by a significant margin. New projects should include permeable pavement, disconnections, and/or rainwater harvesting systems depending on whether the priority of UCB campus administration is maximizing performance or minimizing costs associated with runoff abatement. Disconnections should be implemented whenever possible as they both maximized runoff abatement and minimized the cost per m^3 of abated runoff. However, because they require a pervious surface onto which to redirect runoff and pervious surface area is limited on the UCB campus, disconnections are not a standalone solution to excessive campus runoff. Where disconnections are not feasible, permeable pavement and/or rainwater harvesting systems should be considered. New projects in the northeast quadrant of campus should be prioritized. One potential project is the installation of permeable pavement in Foothill Lot. Because permeable pavement was one of the two most effective LID practices and Foothill Lot is an impervious surface surrounded by steep slopes, this project would likely result in a significant reduction in runoff volume.

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