Rainwater Savings Potential of Prototypical Modular Extensive Green Roofs at UC Berkeley

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Abstract Green roofs are vegetated roof installations comprised of various tiers that provide plant support, drainage, and waterproofing. Extensive green roofs may provide environmental and economic benefits for UC Berkeley and help achieve UC system-wide and campus-specific environmental standards and goals, particularly through water conservation. To assess their potential, this study compares the rainwater savings of prototypical modular extensive green roofs with that of a regular gravel roof. The measures used for comparison are water detention and retention. Simulated precipitation patterns modeled after a local 25-year rainfall event were applied to roof treatments, and runoff rates and volumes were collected and analyzed. The results indicate that for the certain rain event, the extensive green roof modules are more effective than the regular gravel roof model at detaining and retaining water—for detention, 1) runoff from the green roof modules was delayed an average of nine minutes from the start of the rainfall events or more than three times longer than the gravel roof model, 2) the peak runoff rate from the green roof modules averaged 3.3 mL/ sec (about 60% of the rainfall intensity) or 35% less than gravel roof model; for retention, 3) the green roofs were able to withhold an average of 2708 mL (about 80% of the total rainfall) or two times more than the gravel roof model. However, this project only validated the practicality of using this green building technology at the university for water conservation; its relevant economic feasibility is crucial but uncertain.

Introduction

Green building is an innovative practice of sustainable development. It has the aims of "increasing the efficiency with which buildings and their sites use energy, water, and materials, and reducing building impacts on human health and the environment, through better siting, design, construction, operation, maintenance, and removal — the complete building life cycle" (Office of the Federal Environmental Executive 2003). By using a holistic approach, green building confers more economic, environmental, and social benefits than those of conventional building, costs notwithstanding. The practice is federally endorsed, promoted by non-governmental organizations, and has been adopted by local and state institutions (Building Design & Construction 2003). However, green building is still a fledgling enterprise due to financial disincentives, lack of awareness, and insufficient research (U.S. Green Building Council 2003). This project contributes to the limited scientific knowledge of green buildings by examining an environmental benefit provided by a novel green building technology in the context of a state institution.

According to the U.S. Environmental Protection Agency's Green Building Workgroup (2004), composed of U.S. EPA programs designed to address the environmental impacts of the built environment, residential and commercial buildings in the U.S. account for about 39% of total energy use, 12% of total water consumption, 68% of total electricity consumption, and 38% of total carbon dioxide emissions in the country. Furthermore, the construction and demolition of the buildings contribute about 60% of total non-industrial waste generation and can cause health effects including cancer and asthma due to their typically poor indoor environmental quality. Therefore, the built environment has a considerable impact on the economy, environment, and human health.

The practice of green building can offset the intensity of or eliminate the impacts by its economic, environmental, and social benefits imparted throughout the building life cycle from design to removal. The U.S. EPA Green Building Workgroup notes the following advantages: environmentally, green building can "enhance and protect biodiversity and ecosystems, improve air and water quality, reduce waste streams, and conserve and restore natural resources"; economically, it can "reduce operating costs, create, expand and shape markets for green products and services, improve occupant productivity, and optimize life-cycle economic performance"; and socially, the practice can "enhance occupant comfort and health, heighten aesthetic qualities, minimize strain on local infrastructure, and improve overall quality of life" (U.S. EPA April 30 2007). These benefits demonstrate how and why green building can contribute to sustainable development of the built environment.

Recognizing its advantageous aspects, federal agencies, non-governmental organizations, and local and state institutions have endorsed, promoted, and adopted the practice of green building (Building Design & Construction 2003). At the federal level, the Office of the Federal Environmental Executive (OFEE) was created to implement executive orders "promoting sustainable environmental stewardship throughout the federal government" (OFEE April 30 2007); the creation of sustainable buildings by green building is one its focuses. A national non-profit organization, the U.S. Green Building Council (U.S. GBC) has created the Leadership in Energy and Environmental Design (LEED) Green Building Rating System, "the national benchmark for high-performance green buildings [commercial and residential]" (U.S. GBC April 16 2006). LEED encourages and certifies the design, construction, and operation of green buildings, and is adopted by federal, state, and local institutions, including the University of California, Berkeley. The state educational institution has formed the Chancellor's Advisory Committee on Sustainability (CACS) to "promote environmental management and sustainable development at UC Berkeley" (CACS April 16 2006). In its 2005 Campus Sustainability Assessment of its Built Environment, the CACS presents the university's progress in implementing the UC Office of the President's Green Building Policy and Clean Energy Standard (GBCE) [1] by adhering to LEED; UC Berkeley drafted a Sustainable Campus section of its Long Range Development Plan (LRDP) to help meet the GBCE requirements (CACS 2005).

Despite its favorable features, green building is still a fledgling enterprise due to barriers to mainstream acceptance including financial disincentives, lack of awareness, and insufficient research (U.S. GBC 2003). Financially, the practice is hindered by the lack of life-cycle cost assessments, disillusionment of higher initial costs, etc. The lack of awareness of green building is attributed to the fact that most building industry professionals are uninformed about green building in an industry that is wary of innovation. Finally, insufficient research on green building is due to deficient funding appropriated by major research-funding agencies, and an absence of a holistic scientific method that "examines the environmental, engineering, energy, and public health factors involved" in green building (U.S. GBC 2003).

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[1] A UC system-wide policy requiring new campus construction and renovation projects to be LEED Silver-certified.

Although not applying such a method, this research project contributes to the limited scientific knowledge of green buildings by examining an environmental benefit provided by a novel green building technology in the context of a state institution. It investigated the rainwater savings potential of prototypical modular extensive green roofs at UC Berkeley.

Green roofs have been intensively studied and extensively applied across Europe, especially in Germany (Dunnett and Kingsbury 2004). They are vegetated roof installations that provide multiple economic, environmental, and social benefits that exemplify those of green building, especially rainwater management (Villarreal 2006). Hence, the U.S. GBC recognizes green roofs as an appropriate green building technology complying with LEED. In accordance with its sustainability goals, UC Berkeley could apply green roofs on campus construction and renovation projects not only to attain LEED certification, but also to improve water conservation. However, green roof research and application in the U.S. have been limited in scope and scale.

A green roof is a vegetated roof installation comprised of multiple layers that provide plant nourishment and support, drainage, and waterproofing (Green Roofs for Healthy Cities 2006). The make and existence individual layers, notably the substrate, depend on various internal and external factors including species of plants being used, stability of the roof upon which to place, etc. Essentially, green roofs can either be extensive, intensive, or semi-intensive. The three types are distinguished by their emphasis on form or function, design, construction and operation costs, as well as primary benefits. Extensive types focus on function while intensive types on form and thus the latter displays greater plant diversity; extensive types are cheaper to assemble and maintain but are less accessible than intensive types; and extensive types concentrate more on economic and environmental benefits than intensive types that exhibit more aesthetic and social qualities. Semi-intensive green roof types vary between the two extreme types. Regardless of type, green roofs are either loose laid on rooftops layer-by-layer, or pieced together with modules with layers self-contained (Green Roofs for Healthy Cities 2006).

Exemplifying green building benefits, green roofs provide the following services (depending on type): aesthetically, they complement the natural landscape while disrupting the urban scene; socially, they offer therapeutic effects including stress relief; economically, they help extend roof life by providing UV protection and conserve energy by insulating the building envelope; and environmentally, green roofs help mitigate the urban heat island effect by evapotranspiration, restore wildlife habitat by reclaiming space lost to urban development, and help rainwater management by their ability to detain and retain runoff (Mentens *et al*. 2006), "the primary benefit of green roofs due to the prevalence of impervious services" (VanWoert *et al*. 2005).

Rainwater management of a green roof is accomplished by the percolation and absorption of rainwater through and by the soil substrate, interception by the vegetation layer, and its evapotranspiration from both soil and vegetation layers. The processes result in "(1) delaying the initial time of runoff due to the absorption of water in the green roof system [detention]; (2) reducing the total runoff by retaining part of the rainfall [retention]; (3) distributing the runoff over a long time period through a relative slow release of the excess water that is temporarily stored in the pores of the substrate [retention]" (Mentens *et al*. 2006). They also cause a "reduction in the peak discharge [detention]" (Villarreal 2006). In effect, green roofs help delay runoff and reduce its peak discharge, both effects of detention; and reduce total runoff and distribute it over time, both effects of retention.

UC Berkeley could benefit from the application of green roofs in the construction and retrofitting of its buildings. The technology would not only help the university earn LEED certification on individual buildings, but also improve water conservation for the entire campus.

The rainwater management benefit of green roofs would help in "minimizing water use and maximizing [its] on-site conservation and reuse" as stated in the Sustainable Campus section of the university's 2020 Long Range Development Plan (2005) and equally expressed in the Water system section of the 2005 Campus Sustainability Assessment (CACS 2005). Coupled with a rainwater capture system, green roofs could reduce or eliminate potable water use for toilet flushing, irrigation, and heating and cooling by recycling rainwater for use as "gray water," and save money (Green Roofs for Healthy Cities 2006).

Furthermore, green roof rainwater management would help Best Practice HYD-3 and "ensure that there is no net decrease in the amount of water recharged to groundwater that serves as freshwater replenishment to Strawberry Creek, "and also Best Practice HYD-4-e and "ensure that there is no net increase in stormwater runoff from the campus resulting from implementation of the 2020 LRDP" accordant to the LRDP Environmental Impact Report (EIR 2005). Green roofs would prevent combined sewage overflows (CSOs) by reducing likely increases in runoff rate and quantity resulting from the increase of impervious surface areas on campus due to its continual development and also provide rainwater for groundwater recharge by releasing it gradually over time. They would conserve rainwater.

However, research on green roofs in the U.S. is fairly recent and limited, and hence their application across the nation has been restricted. Most studies on the technology have been done in Europe, especially in Germany (Dunnett and Kingsbury 2004). Current scientific literature contains green roof findings on their physical and biological characteristics such as construction (Emilsson and Kaj 2005), vegetation (Monterusso *et al.* 2005), substrate (Sherman 2005), thermal qualities (Castellotti *et al*. 2005, DeNardo *et al.* 2005, Kumar and Kaushik 2005), and life-cycle costs (Wong *et al.* 2003). Still, most studies have focused on green roof rainwater management, because it is the "most important research area in the roof-greening world" (Dunnett and Kingsbury 2004).

To validate the use of green roofs at UC Berkeley, this project investigated the rainwater savings potential of prototypical modular extensive green roofs on the campus. In general, the extensive green roof type (as opposed to the intensive or semi-intensive type) would best produce the economic and environmental effects of water conservation desired by the university as follows: saving money through water reuse, preventing combined sewage overflows, and promoting groundwater recharge. Its modular system (as opposed to a loose-laid system) would be more suitable in both the context of the campus and this study, because it is less expensive and more expeditious to install and maintain due to their simple and flexible design (GreenGrid January 16 2007).

Regarding rainwater savings, an extensive green roof's rainwater-retention capability on a yearly basis has been generally found to be about 45% of total rainfall (DeNardo *et al.* 2005, Mentens *et al*. 2006), while its rainwater-detention capability (specifically its peak discharge reduction) has been found to range from 44% to 65% of peak inflow (DeNardo *et al.* 2005, Villarreal 2006). Life-cycle assessments have mainly focused on green roofs' energy conservation (Saiz *et al.* 2006), and thus an economic analysis of water conservation is not available. Nonetheless, these results are generalized; the rainwater savings potential of a green roof depends on its structure (extensive, intensive, or semi-intensive and corresponding number, composition, and depth of layers used), existing roof slope and length, and the local climactic conditions and precipitation patterns (Dunnett and Kingsbury 2004).

This project corroborated the findings by subjecting roof treatments to the temperate, semi-arid Mediterranean macroclimate experienced at UC Berkeley (LRDP 2005) and its corresponding precipitation patterns for a 25-year rain (Rantz 1971). The roof treatments included vegetated and non-vegetated extensive green roof modules, and a gravel roof model.

I hypothesized that an extensive green roof will produce more rainwater savings than a regular roof at UC Berkeley during and after local 25-year rainfall events. In effect, the modular extensive green roof will detain and retain rainwater by delaying runoff and reducing its peak discharge (detention), and reducing the amount of runoff and distributing it over time (retention) more effectively than the regular gravel roof. The findings contribute to general green building and specific green roof knowledge. They also help ascertain whether green roofs would be a practical green building technology for UC Berkeley to apply in its construction and renovation projects to meet the UC system-wide Green Building Policy and Clean Energy Standard and to realize its campus-specific water conservation goals as a best management practice (BMP).

Methods

Study site and duration The project was conducted at the North Greenhouse of the Oxford Tract, a College of Natural Resources campus research facility located across from the northwest corner of UC Berkeley. The greenhouse was climate-controlled for temperature and humidity, providing a constant environment aside from the variability in solar radiation and the simulated precipitation. The project proper lasted a couple of months, starting in March 2007 and ending in April 2007.

Roof Parameters The following three roof treatments were tested: a vegetated extensive green roof module, a non-vegetated counterpart, and a gravel roof model. The vegetated extensive green roof module (henceforth known as "plant module") (Fig.1) was the featured treatment, while the non-vegetated counterpart (henceforth known as "soil module") (Fig. 2) was a control for the variation of vegetation possible on green roofs (plant species and number used, and their spatial arrangement) (VanWoert *et al*. 2005). The gravel roof model (henceforth known as "gravel model") (Fig. 3) represented a regular roof and served as a control to the previous two treatments.

Both the plant and soil modules were GreenGrid® modular extensive green roof units supplied by Weston Solutions, Inc. and produced by ABC Supply, Inc., made of polyethylene, measured 61 cm x 61 cm x 10 cm, and contained a proprietary organic and inorganic media mixture (soil substrate) (GreenGrid January 16 2007). In addition, the plant module contained a vegetation layer composed of succulent *Sedum* species and a California native plant supplied by Mountain Crest Gardens, suited to the Mediterranean macroclimate and green roof microenvironment (Mountain Crest Gardens February 16 2007); e.g., 4 tri-color *Sedum acre* ‘Aureum,’ 8 *Rosularia platyphylla*, and 3 *Festuca glauca* ‘Elijah-Blue.’

The gravel model was comprised of wood and contained ASTM C-33 compliant all-purpose gravel purchased from hardware stores. I constructed and waterproofed a wooden catchment to act as an impervious roof surface, having the same dimensions as the green roof modules. In compliance with ASTM International standards, the all-purpose gravel resembled the gravel used on some roofs on the campus (Stilgenbauer 2007, pers. comm.). The gravel layer laid within was .64 cm deep as opposed to the 10 cm-deep soil substrate in the green roofs.

Installed on rooftops, the green roof modules were placed within similar catchments. All catchments had a 7.6 cm x 7.6 cm square outlet in one corner and were inclined at a 2% slope to facilitate outflow of runoff. Considering the experiment’s physical limitations, the outlet size and slope percentage were arbitrarily chosen to produce optimum outflow (Stilgenbauer 2007, pers. comm.). Acccording to Dunnett and Kingsbury (2004), a maximum slope of 17% is the recommended limit before requiring additional slope stabilization measures.

Figure 1. Vegetated modular extensive green roof, “plant module”

Figure 2. Non-vegetated modular extensive green roof, “soil module”

Figure 3. gravel roof model, “gravel model”

Rainfall parameters The simulated precipitation was administered via a pair of suspended nozzles. They were calibrated to deliver the corresponding intensities of 5, 10, and 15-minute rainfall durations for a rain with a 25-year recurrence interval (25-year rain) based on the 2020 Long Range Development Plan's Environmental Impact Report (2005) and the following hydrological data: the time-of-travel equation (Ferguson and Debo 1990), and precipitation depth-duration-frequency data for the San Francisco Bay region (Rantz 1971).

The 2020 LRDP Environmental Impact Report (2005) states that "any new development in the Campus Park or Hill Campus that might increase stormwater runoff may cause flooding problems within [Berkeley] City's drain system and along lower Campus Park elevations near the channel," because the capacity of the drain system at Oxford St. where Strawberry Creek leaves the campus will be exceeded by 25% during a 25-year rain event. Under that condition, combined sewage outflows will be exacerbated by campus construction, but may be mitigated by green roofs capable of producing rainwater savings during a 25-year rain event.

Accounting for the varying roof dimensions of current and future buildings, 5, 10, and 15-minute durations of the 25-year rain event were tested. The time-of-travel equation ($Tc = Hl/ V$) equates the time of concentration (duration) (Tc) as a function of the hydraulic length (Hl) and the velocity (V) pertaining to a drainage area's slope length and surface material, and attendant runoff (Ferguson and Debo 1990). The hydraulic length is the length along which the runoff takes the longest possible time to reach an outlet within the drainage area and depends on the area's slope length; the velocity is the rate of distance traveled by the runoff over time within the drainage area and depends on the area's surface material. In this project, the drainage areas were the individual catchments that had an impervious surface similar to a paved one, so its velocity was fixed. However, their hydraulic lengths were variable, as the modular extensive green roof units are flexible and can cover a range of roof dimensions; similarly, the gravel roof model was a sample area. Therefore, three convenient slope lengths were chosen (30.5 m, 61 m, and 152.4 m) to produce the three corresponding times of concentration, or rainfall durations used.

Rantz's (1971) precipitation depth-duration-frequency data for the San Francisco Bay region correlates the 25-year rain event and associated durations with rainfall depths. To produce .635 cm of rain in 5 minutes, the nozzles were calibrated to deliver an intensity of 7.87 mL of water per second; for .99 cm of rain in 10 minutes, the nozzles delivered 6.14 mL of water per second; to administer 1.24 cm of rain in 15 minutes, the nozzles delivered 5.14 mL of water per second.

Procedures The three roof treatments were individually tested on alternate days (e.g., gravel one day, then soil the next, followed by plant the following day, repeat) to allow time for them to dry and horizontally rotated about center counter-clockwise for replication before each trial. Rainfall durations were cycled every three roof treatments for consistency (e.g., 5-minute for one sequence of gravel, soil, and plant, then 10-minute the next sequence, followed by 15-minute the following sequence, repeat). Trial conditions consisted of subjecting a certain roof treatment to a certain rainfall duration per day. In total, 36 replicates were completed (Table 1).

Table 1. Parametric test table: 4 replicates per roof treatment x rainfall duration trial condition

		25-year Rainfall duration			
		5-minute	10-minute	15-minute	Total
Roof treatment	Gravel model	4	4	4	12
	Soil module	4	4	4	12
	Plant module	4	4	4	12
	Total	12	12	12	36

The only measurement collected per trial was the amount of time transpired (sec) per every 50 mL of runoff; i.e., a rate of time per volume of runoff. Conversely, measuring the amount of runoff volume (mL) per every set length of time (e.g., a rate of runoff volume per 10 seconds) was impractical due to physical limitations (recording the volume accurately, noting it at the exact time, etc.). The measurements were collected during entire rainfall durations and for thirty minutes afterwards. A couple of 500 mL graduated cylinders and a stopwatch were used to gauge the amount of runoff and record the time. The runoff flowed into the graduated cylinders from the catchment's outlet via a plastic funnel (Fig. 4).

Figure 4. Experimental setup

Post-trial, the measurements were entered into Microsoft Excel where detention and retention effects were calculated. For detention, the critical effect was the peak runoff rate. For retention, the crucial effect was the amount of water withheld. In addition, the following effects were also derived for each trial condition: time to initial runoff (detention), and volume of total runoff (retention).

Multiple One-way Analysis of Variance (One-way ANOVA) tests were used to test for statistical significance of the individual effects as independent factors across the three roof treatments (gravel model (n = 4), soil model (n = 4), and plant model (n = 4)) per rainfall duration.

Results

The following results illustrate the rainwater detention and retention capabilities of the vegetated extensive green roof module, the non-vegetated counterpart, and the gravel roof model. The tables and hydrographs summarize the detention effects of delayed runoff and reduction of peak runoff rate (Table 2) (Fig. 6); and the retention effect of withholding water[2] (Table 3) (Fig. 5) for each roof treatment under the three rainfall durations (5-, 10-, and 15-minute). Overall, the data show that the rainwater detention and retention capabilities of the extensive green roof modules were more effective than those of the regular roof model during and after rainfall events with a local 25-year recurrence interval.

Detention The times to initial runoff were greater in both extensive green roof modules than the regular gravel roof model for every rainfall event (Fig. 7). During the 5-minute rain duration, the gravel model began its runoff shortly after two minutes from the beginning of the precipitation, while both the soil and plant modules did not exhibit any runoff for the entire period including the thirty-minute follow-up. However, all roof treatments exhibited runoff for the 10- and 15-minute rainfall events. The regular roof model began its runoff at about the same time (between two to three minutes) after the start of both rain durations during which the green roof modules did not display any runoff until after eight to ten minutes (about three to four times slower than the gravel model). Yet between the green roof modules, the plant module had a longer time to initial runoff than the soil module (by about 37%) in the 10-minute rain but a slightly shorter time than the soil module (by about 2%) in the 15-minute rain.

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[2] The other effect of distributing the withheld water over time was not discernable given the short trial durations.

Table 2. Summary of rainwater detention effects: values in parentheses are % with respect to R

Roof treatment Rainfall event	Rainfall intensity *R* (mL/ s)	Time to initial runoff (s)	Peak runoff rate (mL/ s)	 (%)	Detention (mL)
Gravel					
5-minute	7.87	132	6.2	79	711
10-minute	6.14	166	5.7	93	429
15-minute	5.14	184	5	98	585
Soil					
5-minute	7.87	n/ a	n/ a	n/ a	2361
10-minute	6.14	489	2.6	43	2782
15-minute	5.14	514	3.9	76	2483
Plant					
5-minute	7.87	n/ a	n/ a	n/ a	2361
10-minute	6.14	572	2.1	35	3291
15-minute	5.14	504	4.5	88	2447

Table 3. Summary of rainwater retention effects: values in parentheses are % with respect to V

Roof treatment Rainfall event	Total rainfall *V* (mL)	Total runoff (mL)	Water withheld (mL)	 (%)
Gravel				
5-minute	2372	1063	1309	56
10-minute	3616	2274	1342	38
15-minute	4563	3314	1249	28
Soil				
5-minute	2361	0	2361	100
10-minute	3698	833	2865	78
15-minute	4580	1789	2792	61
Plant				
5-minute	2361	0	2361	100
10-minute	3861	443	3419	89
15-minute	4632	2186	2447	53

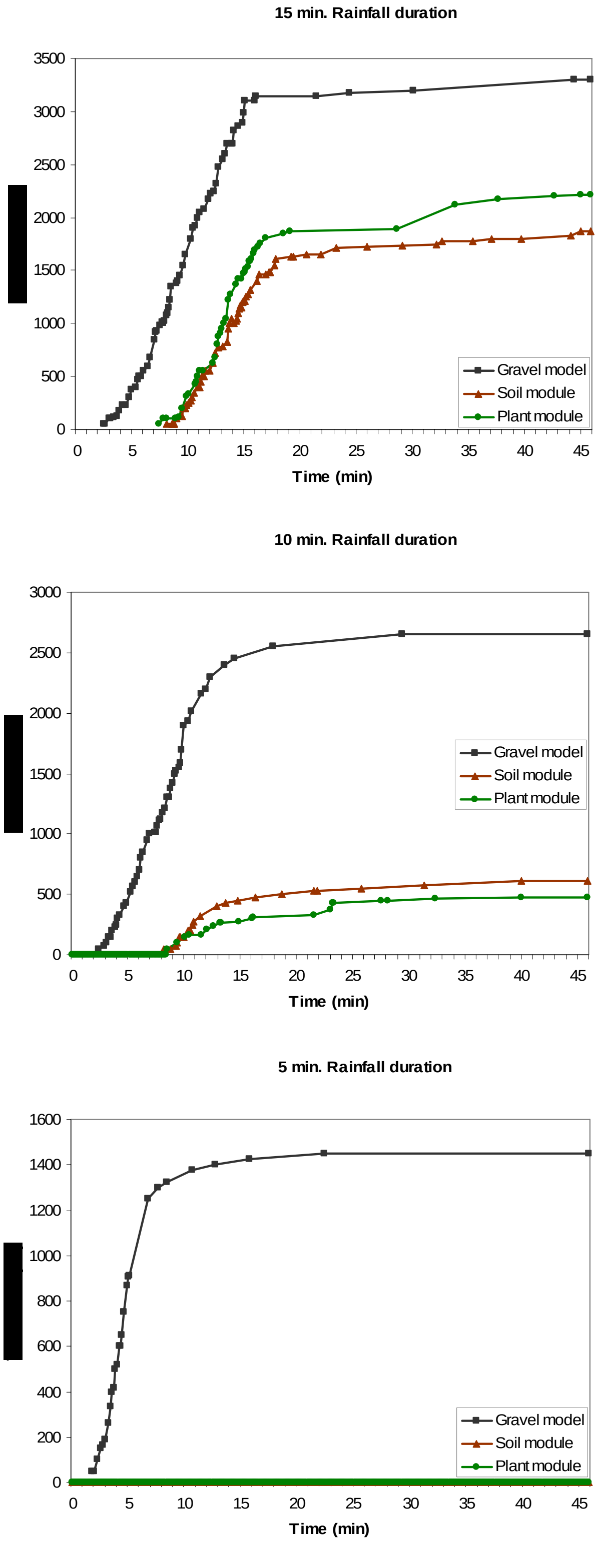

Figure 5. Averaged total runoff (mL) for all rain events for each roof treatment

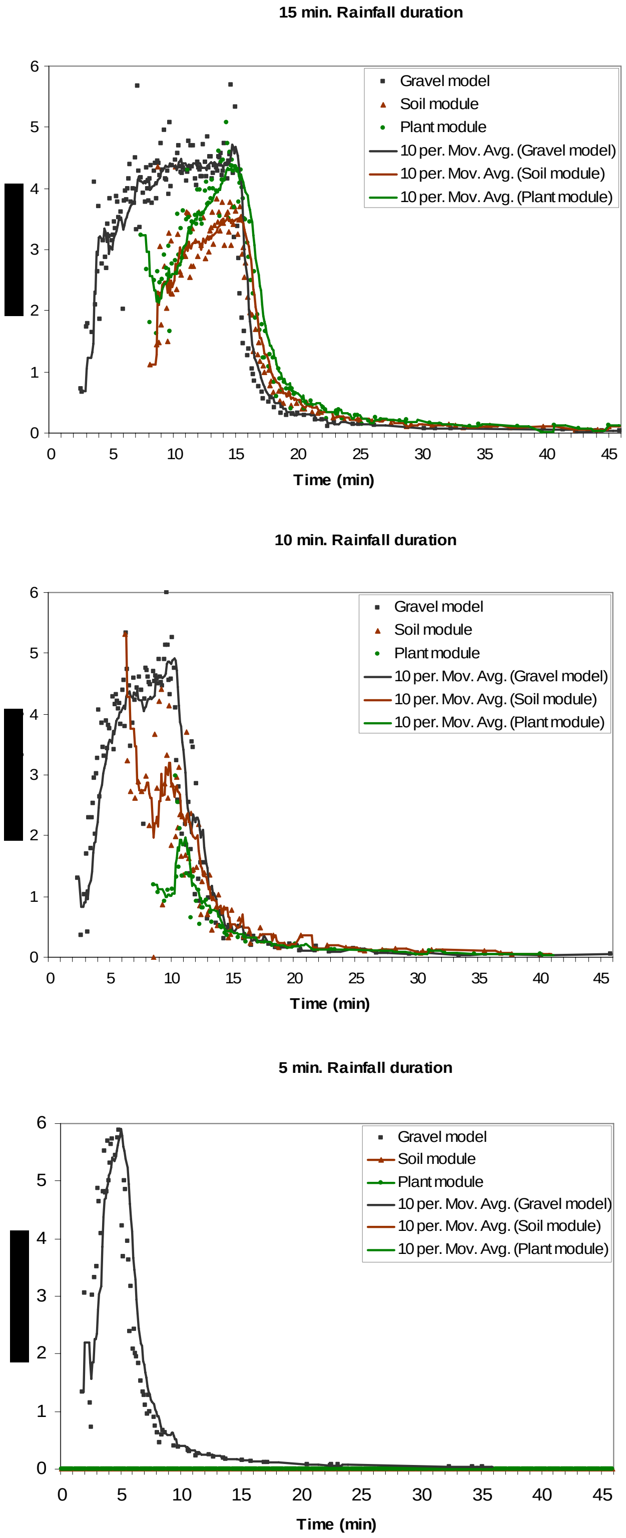

Figure 6. Averaged runoff rate (mL/ s) for all rain events for each roof treatment; moving average used as trendline (avg. every 10 min.)

The peak runoff rates were greater in the regular gravel model than both extensive green roof modules for every rainfall event (Fig. 8). During the 5-minute rain duration, the gravel model exhibited a peak runoff rate of about 80% of the corresponding rainfall intensity, while both the soil and plant modules did not have any runoff for the entire period including the thirty-minute follow-up. However, all roof treatments demonstrated peak runoff rates for the 10- and 15-minute rainfall events. For both rain durations, the gravel model exhibited peak runoff rates of more than 90% of the corresponding rainfall intensities; in other words, the runoff was produced from the treatment nearly as fast as the rain was depositing on it. The soil and plant modules both had substantially reduced peak runoff rates (about less than 50% than the gravel model's) for the 10-minute rain; the plant module had a somewhat lower peak runoff rate than the soil module (by about 19%). Yet, all roof treatments had peak runoff rates approaching or exceeding 80% of the intensity of the 15-minute rain; the gravel model was effectively equal to it, and both green roof modules experienced at least a doubling of their peak runoff rates from the 10-minute rain. Then again, the soil module had the lowest peak runoff rate in the 15-minute rain.

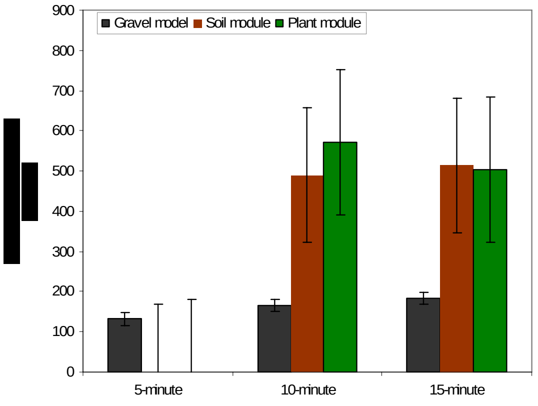

Figure 7. Averaged time to initial runoff (s) for all rain events for each roof treatment. Error bars represent standard error. 5-min.: $P < 0.0001$; 10-min.: $P < 0.0001$; 15-min.: $P < 0.0001$ (One-way ANOVA)

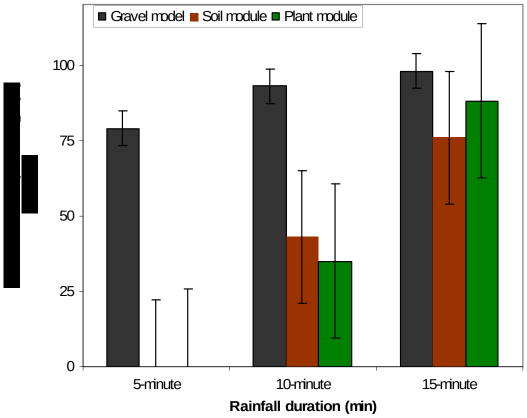

Figure 8. Averaged peak runoff percentage (%) for all rain events for each roof treatment. Error bars represent standard error. 5-min.: $P < 0.0001$; 10-min: $P = 0.0086$; 15-min.: $P = 0.17$ (One-way ANOVA)

Retention The total amount of water withheld during and after every rainfall event was greatest for both green roof treatments than the regular roof treatment (Fig. 7). Both soil and plant modules withheld the entire amount of water produced during the 5-minute rain, while the gravel model loss nearly half of it. The percentage of water withheld per roof treatment systematically decreased across the 10- and 15-minute rains; the gravel model decreased gradually and remained above 25%, but the green roof modules exhibited sharper losses, particularly in the 15-minute rain when they loss nearly half of the water. The plant module withheld more water than the soil module in the 10-minute rain (by about 14%), but less than the soil module in the 15-minute rain (by about 9%). Still, the green roof modules withheld about twice the amount of water than the gravel roof model across all rainfall durations.

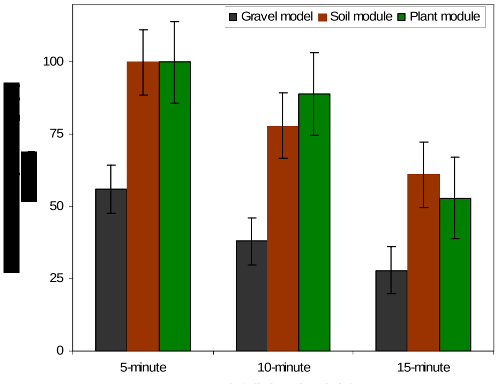

Figure 9. Averaged retention percentage (%) for all rain events for each roof treatment. Error bars represent standard error. 5-min.: $P = 0.0002$; 10-min.: $P < 0.0001$; 15-min.: $P < 0.0001$ (One-way ANOVA)

Discussion

On the whole, my hypothesis was supported. The modular extensive green roofs were more effective than the gravel roof at detaining rainwater by delaying runoff and reducing its peak discharge and retaining the rainwater by reducing the amount of runoff. Despite the discrepancy of those capabilities between the soil and plant modules, both green roofs possessed more rainwater savings potential than the regular roof during and after local 25-year rainfall events. Green roofs, specifically modular extensive types, have been shown to be a practical green building technology for UC Berkeley to apply in its development to meet both system-wide and campus-specific environmental standards and goals as a best management practice. However, the economic feasibility of using green roofs on campus remains uncertain and prompts further research.

The three most important summary statistics of the results were the following: concerning detention, 1) runoff from the green roof modules was delayed an average of nine minutes from the start of the rainfall events or more than three times longer than the gravel roof model, 2) the peak runoff rate from the green roof modules averaged 3.3 mL/ sec (about 60% of the rainfall intensity) or 35% less than gravel roof model; regarding retention, 3) the green roofs were able to withhold an average of 2708 mL (about 80% of the total rainfall) or two times more than the gravel roof model. The results corroborated the findings of other studies regarding the rainwater savings capabilities of extensive green roofs (DeNardo *et al.* 2005, Mentens *et al*. 2006, and Villarreal 2006). It seems that the detention and retention capabilities of the green roofs are primarily inbuilt and function relatively alike in spite of differences in the green roof structure, existing roof slope and length, and the local climatic conditions and precipitation patterns—yet there were differences of those capabilities between the two green roof modules.

Regarding their structure, a previous study found that the soil substrate layer affects rainwater detention and retention to a greater extent than the vegetation layer (VanWoert *et al*. 2005). The results reflect the finding, as the soil module outperformed the plant module at both detaining and retaining rainwater during the 15-minute rainfall event. The rain could have splashed off of the plants in the plant module and out of its catchment. The results could have been due to the composition and arrangement of the plants themselves in the vegetation layer. The plants were plugs that were not mature with fuller foliage height and cover, and root penetration to provide more interception and evapotranspiration[3] of the rainwater.

About existing roof slope, multiple studies concluded that it has no effect on the rainwater savings potential of the green roof (VanWoert *et al*. 2005, Villarreal 2006). Thus, the arbitrary slope percentage used for all treatments did not confound the results.

However, concerning roof length, the results show that the detention and retention capabilities of green roofs decrease in effectiveness as the roof length increases for a given rain recurrence interval. The results indicate that for roofs over 150 m in length, the rainwater savings potential of the overlaying green roof would gradually approximate those of a regular gravel roof and not be of any additional benefit. This finding has implications on the roof dimensions and in turn, the building size of future developments on campus designed for the use of green roofs to manage rainwater.

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[3] This effect was not discernable given the short trial durations.

Though practical for water conservation, the application of green roofs at UC Berkeley for that or other environmental, economic, or social benefits would require further research to help determine its feasibility. As demonstrated by this project, extensive green roofs on new construction or existing buildings in the Campus Park or Hill Campus would relieve potential combined sewage overflows in the City of Berkeley's drainage system during a 25-year rain, and help restore Strawberry Creek's groundwater supply in accordance to the 2020 Long Range Development Plan's Environmental Impact Report. Furthermore, combined with a rainwater capture system, they would recycle rainwater for use as "gray water" for toilet flushing, irrigation, and heating and cooling, thereby conserving potable water and saving money as preferred by the LRDP. Finally, green roofs would help earn LEED certification as mandated by the UCOP Green Building Policy and Clean Energy Standard.

Yet, the exact financial costs and benefits of adopting green roofs on campus are unknown. Multiple and mixed factors are involved in the determination of a green roof's economic feasibility including its design, construction, and operation costs, the monetary value of its rainwater savings, and other benefits—essentially, its entire life-cycle. Therefore, economic life-cycle assessments (LSAs) are necessary to carry out should UC Berkeley consider conducting its own experiment on the novel green building technology to promote a sustainable and holistic approach to its built environment.

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