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6.   GREEN ROOF DESIGN

The first primary topic of this thesis is to investigate the application of a green roof to the SLCC. SmithGroup's original schematic design includes a roof terrace and garden on the second story roof; it features views of campus and the Washington city skyline beyond (Figure 6.1). Access to this space requires an extended balcony in the atrium and egress stairway at the far end of the terrace. Instead of pursuing this design, the value engineering process eliminated the roof garden; the costs of the additional structure, access, and green roofing were deemed to great for the value of this design feature. The final SLCC design includes a highly reflective "cool roof" instead (Figure 6.2).

This section investigates and compares the thermal properties of the original "cool roof" and the proposed green roof. Implications on stormwater retention and the urban heat island effect are also addressed in this section. Structural and acoustic implications are studied as breadth topics in Sections 8 and 9, respectively.
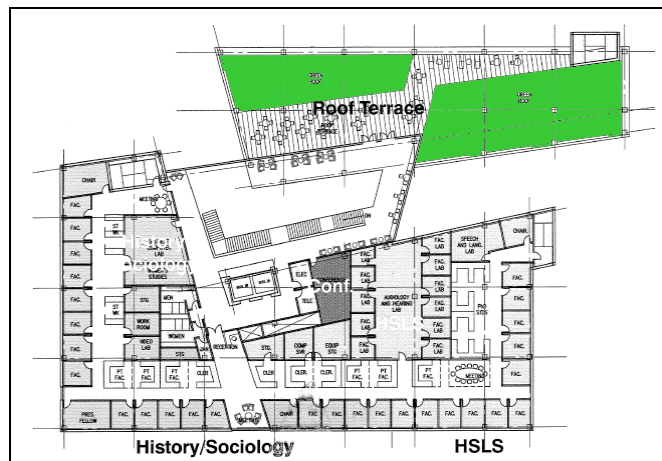

Figure 6.1: Schematic Design Phase proposal for green roof (SmithGroup).

Figure 6.2: Example of a cool roof (fypower.org).

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6.1.   EXISTING ROOF DESIGN

The existing roof is designed as a "cool roof" or highly reflective roof. This selection is based on reducing the heat gain through the roof and to earn a LEED point for reducing the urban heat island effect. A cool roof is essentially a typical roof with a highly reflective (white) membrane that reflects approximately 80% of incoming solar radiation. A typical roof by contrast absorbs approximately 80% of incoming solar radiation. Both roofs re-emit approximately 90%-95% of incoming infrared radiation. The net heat gain for a cool roof is thus much less with a highly reflective roof than with a traditional roof (Gaffin, et al.). See Figure 6.3 for typical material solar absorptivity and emissivity ratios. Note that the approximation for a green roof solar reflectance includes the effect of evapotranspiration.
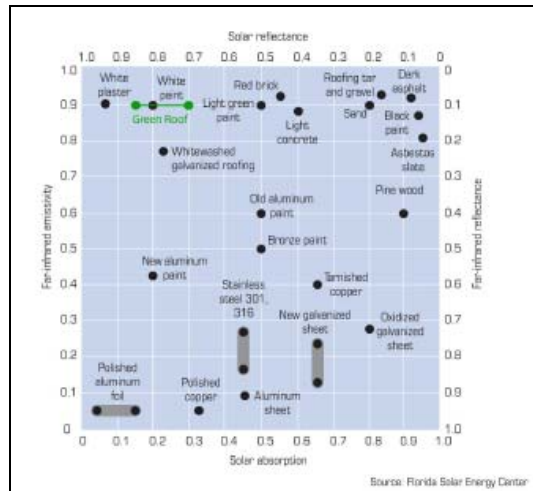

Figure 6.3: Typical material solar absorptivity and emissivity ratios (Gaffin, et al.).

The existing roof is composed of either 18GA or 20GA 1-½ in. steel roof deck, eternal gypsum board, 3in rigid insulation, cover board, and a modified bituman roof membrane with a high albedo coating (Figure 6.4).
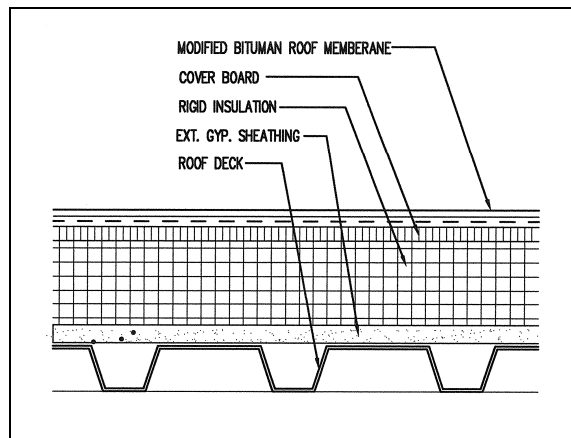

Figure 6.4: Existing roof construction (SmithGroup).

6.2.   PROPOSED ROOF DESIGN

There are two fundamental forms of green roofs: intensive and extensive. Intensive green roofs typically have soil beds greater than 4in deep and larger plants that require deep root structures. Some intensive roofs even include trees, though many are only designed for grasses, flowers and small shrubs. These roofs typically require the structure to carry gravity loads of 50psf or more. Intensive green roofs also require more sophisticated drainage and irrigation systems and more frequent maintenance in comparison to extensive green roofs (United States Environmental Protection Agency).

Extensive green roofs, instead, are more utilitarian in nature. The soil on an extensive green roof is usually less than 4in deep and the plantings are typically sedums, mosses, and other plants that require shallow roof structures. These plants also need to be drought resistant in order to function all year. Extensive green roofs can sometimes be retrofitted on existing roof structures because the structure may be oversized (Gifford).

This thesis investigates the application of an extensive green roof for several reasons. The extensive green roof has positive influences on the building cooling load, stormwater management, urban heat island effect, aesthetics, and acoustics without as negative an impact on the structure and first cost.

The construction of a green roof is similar to a typical roof with the addition of drainage layer and root barrier, soil substrate, and plantings (Figure 6.5).
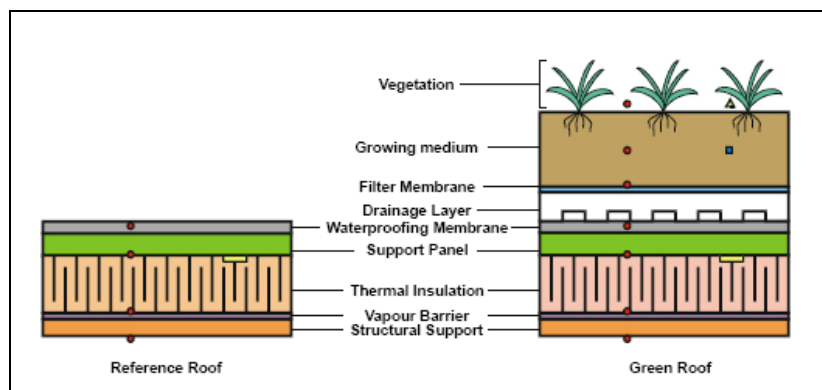

Figure 6.5: Construction of original roof and green roof.

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The scope of the proposed extensive green roof includes the entire roof except for areas with access hatches and mechanical equipment (Figure 6.6). Unlike the schematic design for a roof terrace, this 24,000SF area is mostly unoccupied except for routine maintenance.
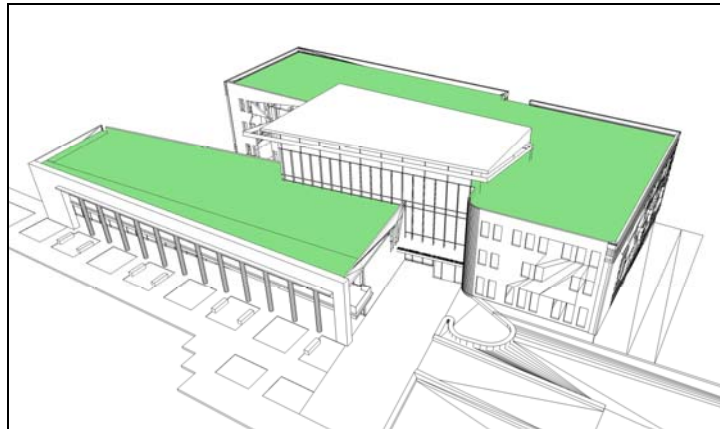

Figure 6.6: Scope of proposed green roof.

DC Greenworks is a full-service green roof design, installation, and consulting company in Washington, DC. According to their website (dcgreenworks.org) and Dawn Gifford, Executive Director of DC Greenworks, the preferred plant types for green roofs in Washington are from the *sedum* genus. These plants typically have high water retention to resist drought and require minimal maintenance.

The proposed green roof design for the SLCC consists of a 4in thick soil substrate and allows several types of plants such as the sedum kamtschaticum (Figure 6.7) – a fleshy 6in. tall plant with a midsummer bloom and high drought tolerance – to grow throughout the year (greenroofplants.com).

Figure 6.7: Sedum kamtschaticum applied to a green roof project (greenroofplants.com).

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6.3.   THERMAL PERFORMANCE

A green roof can have a positive influence on the thermal performance of a building. A common misconception is that the soil and plant material act as additional thermal insulation. Instead, green roofs perform a complex energy balance throughout the day. Incident and reflected solar radiation, incident and emitted infrared radiation, convective heat losses, latent heat losses (evapotranspiration), and conductive heat losses vary somewhat independently throughout the day (Figure 6.8) (Gaffin, et al.).

The evapotranspiration is what truly makes a green roof unique from other roofing options. Also, the green roof acts as a thermal mass by storing thermal energy from the day and releasing it at night.

A mathematical analysis of this energy balance finds the conductive heat gain (i.e. cooling load) on the building. The methodology and calculations for this energy balance may be found in sections 6.4 and 6.4.1.
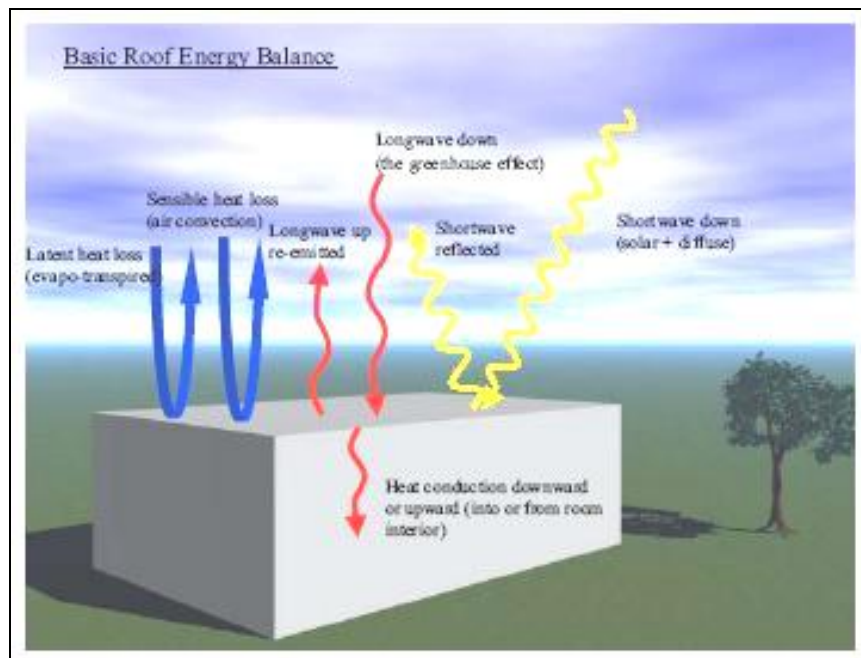

Figure 6.8: Energy balance of a green roof (Gaffin, et al.).

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6.4. METHODOLOGY

An energy balance of shortwave radiation, longwave radiation, convection, latent heat loss, and conduction approximates the heat gain through the roof. This heat gain is assumed to be equal to the additional cooling load on the building mechanical system.

In order to form a more accurate model one month bins are analyzed for this energy balance per square foot of green roof space. Incident solar radiation is calculated using the clear sky model. From this, annual averages are calculated using various average weather data for each month. Then annual heat gain for the entire building is calculated using the annual average heat gain per square foot of roof area. The process is repeated for the original cool roof and for a typical roof. The following governing equations apply (Gaffin, et al.):

Solve for:	Equation	[Units]
Heat Gain (conductive)	$Q_{cond} = Q_{SW,in} - Q_{SW,out} + Q_{LW,in} - Q_{LW,out} - Q_{conv} - Q_{lat}$	[W/m^2]
Incident Shortwave Radiation	$Q_{SW,in} = G_b + G_d$	[W/m^2]
Beam Solar Radiation	$G_b = G_{on}\, \tau_b\, \cos(\Theta_z)$	[W/m^2]
Diffuse Solar Radiation	$G_d = G_{on}\, \tau_d\, \cos(\Theta_z)$	[W/m^2]
Direct Solar Radiation	$G_{on} = Gsc\, [\, 1 + 0.033 \cos(360n/365)\,]$	[W/m^2]
Beam Solar Transmittance	$\tau_b = a_0 + a_1 \exp[\, -k\, /\cos(\Theta_z)\,]$	[-]
Diffuse Solar Transmittance	$\tau_d = 0.271 - 0.294\, \tau_b$	[-]
Transmittance Coefficients	$a_0 = r_0\, [\, 0.4237 - 0.00821(6-A)^2\,]$	[-]
	$a_1 = r_1\, [\, 0.5055 - 0.00595(6.5-A)^2\,]$	[-]
	$k = r_k\, [\, 0.2711 - 0.01858(2.5-A)^2\,]$	[-]
Reflected Shortwave Radiation	$Q_{SW,in} = \alpha\, Q_{SW,in}$	[W/m^2]
Incident Longwave Radiation	$Q_{LW,in} = (\, 0.605 + 0.048\, e^{0.5}\,)\, \sigma\, T_{air}^4$	[W/m^2]
Emitted Longwave Radiation	$Q_{LW,out} = \varepsilon\, \sigma\, T_{roof}^4$	[W/m^2]
Convective Heat Loss (u > 1.75)	$Q_{conv} = \gamma_1\, u^{0.8}\, (T_{roof} - T_{air})$	[W/m^2]
Convective Heat Loss (u ≤ 1.75)	$Q_{conv} = \gamma_2\, (T_{roof} - T_{air})$	[W/m^2]
Latent Heat Loss (Evapotranspiration)	$Q_{lat} = Q_{conv}\, /\, B$	[W/m^2]

Variable/Constant	Symbol	Value	[Units]
Zenith Angle	Θ_z	varies	[°]
Solar Constant Shortwave Radiation	Gsc	1367	[W/m^2]
Altitude above sea level	A	0.125	[km]
Albedo	α	varies	[-]
Water Vapor Pressure	e	varies	[millibars]
Stefan-Boltzman Constant	σ	5.67x10^{-8}	[W/m^2-K^4]
Emissivity	ε	varies	[-]
Convective Heat Transfer Coefficient	γ	varies	[W/m^2-K]
Average Wind Speed	u	varies	[m/s]
Bowen Ratio	B	varies	[-]

ASSUMPTIONS

- The maximum and minimum heat transfer equal the peak daily and base nightly heat gain through the roof, respectively.
- The daily profile of the net heat transfer is a sinusoidal curve between these peak and base values.
- The peak and base values are assumed to be twelve (12) hours apart, with the peak at 2:00pm for the typical and cool roof, and 4:30pm for the green roof (to account for thermal mass).
- The total conductive heat transfer through the roof is equal to the heating/cooling load on the mechanical system.
- Because the clear sky model is used, all days are assumed to have clear skies and there is no shade on the roof.
- Shortwave solar radiation at night is assumed to be 0 W/m^2.
- The roof temperatures are approximated from research results at the Penn State Center for Green Roof Research (Gaffin, et al.).
- The albedo of the green roof is assumed to be 0.25, 0.78 for the cool roof, and 0.2 for a typical roof (Nobel).
- The emissivity of all roofs is assumed to equal 0.9 (Gaffin, et al.).
- The Bowen Ratio is approximated as 0.17 (Gaffin).
- Weather data is provided from the Department of Meteorology at the University of Utah.

6.4.1.   CALCULATIONS

Beam (G_b) and diffuse (G_d) incident solar shortwave radiation calculated using the clear sky model for each month can be seen in Table 6.1. The energy balance of the green roof required input data for the site conditions throughout the year. This data may be found in Table 6.2. Finally, the hourly annual average heat transfer and net heat gain per square meter may be seen in Table 6.3 and Figure 6.9. Breakdowns of average heat gain for each month and roof type for day and night conditions can be found in Appendix A.

Average Peak Instantaneous Solar Radiation

MONTH	n	δ	Θz	G_{on} [W/m²]	G_b [W/m²]	G_d [W/m²]	G_{total} [W/m²]
JANUARY	17	-20.92	59.80	1410.19	417.29	69.57	486.86
FEBRUARY	47	-12.95	51.83	1398.13	508.19	84.72	592.91
MARCH	75	-2.42	41.30	1379.46	609.61	101.63	711.24
APRIL	105	9.41	29.47	1356.42	694.67	115.81	810.48
MAY	135	18.79	20.09	1336.15	738.13	123.06	861.19
JUNE	162	23.09	15.79	1324.67	749.77	125.00	874.77
JULY	198	21.18	17.70	1323.49	741.65	123.65	865.30
AUGUST	228	13.45	25.43	1335.03	709.23	118.24	827.47
SEPTEMBER	248	6.18	32.70	1347.65	667.09	111.22	778.31
OCTOBER	288	-9.60	48.48	1377.96	537.29	89.58	626.87
NOVEMBER	318	-18.91	57.79	1398.13	438.34	73.08	511.41
DECEMBER	344	-23.05	61.93	1409.20	390.05	65.03	455.07

Location: Washington, DC

A [km] = 0.125   φ = 38.88   ω = 0

τ_b = 0.588 a_0^* = 0.14033 r_0 = 0.97 a_0 = 0.13612

τ_d = 0.098 a_1^* = 0.74731 r_1 = 0.99 a_1 = 0.73984

G_{sc} [W/m²] = 1367.0 k^* = 0.37590 r_k = 1.02   k = 0.38342

Table 6.1: Monthly average peak instantaneous solar radiation.

Monthly Average Ambient Conditions for Washington, DC

Month → Energy Flux Mode↓	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
T_{OA} [K]:	278.9	280.9	286.8	292.4	297.7	302.4	304.5	303.7	299.9	293.8	287.8	281.5	292.6
T_{OA} [°F]:	42.3	45.9	56.5	66.7	76.2	84.7	88.5	86.9	80.1	69.1	58.3	47	66.9
T_{roof} [K]:	283.2	285.2	291.0	296.7	302.0	306.7	308.8	307.9	304.2	298.0	292.0	285.8	296.8
T_{roof} [°F]:	50	53.6	64.2	74.4	83.9	92.4	96.2	94.6	87.8	76.8	66	54.7	74.6
T_{RA} [K]:	295.4	295.4	295.4	298.7	298.7	298.7	298.7	298.7	298.7	298.7	295.4	295.4	297.3
T_{RA} [°F]:	72	72	72	78	78	78	78	78	78	78	72	72	75.5
P_{vapor} [millibars]:	0.0089	0.0101	0.0151	0.0218	0.0298	0.0384	0.0426	0.0408	0.0336	0.0237	0.0161	0.0106	0.0244
U_{wind} [m/s]:	4.5	4.6	4.9	4.7	4.2	4.0	3.7	3.6	3.8	3.9	4.2	4.3	4.2
Direct Solar (G_b):	417.29	508.19	609.61	694.67	738.13	749.77	741.65	709.23	667.09	537.29	438.34	390.05	600.4
Diffuse Solar (G_d):	69.57	84.72	101.63	115.81	123.06	125	123.65	118.24	111.22	89.58	73.08	65.03	100.1
Avg. Precipitation [in]:	2.72	2.71	3.17	2.71	3.66	3.38	3.80	3.91	3.31	3.02	3.12	3.12	38.63

Table 6.2: Monthly average ambient conditions for Washington, DC.

Average Daily Net Roof Heat Flux [BTU/hr-ft^2]

	Green Roof	Cool Roof	Typical Roof
Peak (Day)	-54.45	-21.87	106.92
Average 24hr	**-79.09**	**-49.83**	**14.57**
Base (Night)	-103.72	-77.78	-77.78
Δ Heat Flux	49.27	55.91	184.70

Hour of Day	Green Roof	Cool Roof	Typical Roof
0	-88.52	-74.04	-65.41
1	-94.09	-76.83	-74.64
2	-98.63	-77.78	-77.78
3	-101.85	-76.83	-74.64
4	-103.51	-74.04	-65.41
5	-103.51	-69.59	-50.73
6	-101.85	-63.80	-31.61
7	-98.63	-57.06	-9.33
8	-94.09	-49.83	14.57
9	-88.52	-42.59	38.47
10	-82.30	-35.85	60.74
11	-75.87	-30.06	79.87
12	-69.66	-25.61	94.54
13	-64.09	-22.82	103.77
14	-59.54	-21.87	106.92
15	-56.33	-22.82	103.77
16	-54.66	-25.61	94.54
17	-54.66	-30.06	79.87
18	-56.33	-35.85	60.74
19	-59.54	-42.59	38.47
20	-64.09	-49.83	14.57
21	-69.66	-57.06	-9.33
22	-75.87	-63.80	-31.61
23	-82.30	-69.59	-50.73
24	-88.52	-74.04	-65.41

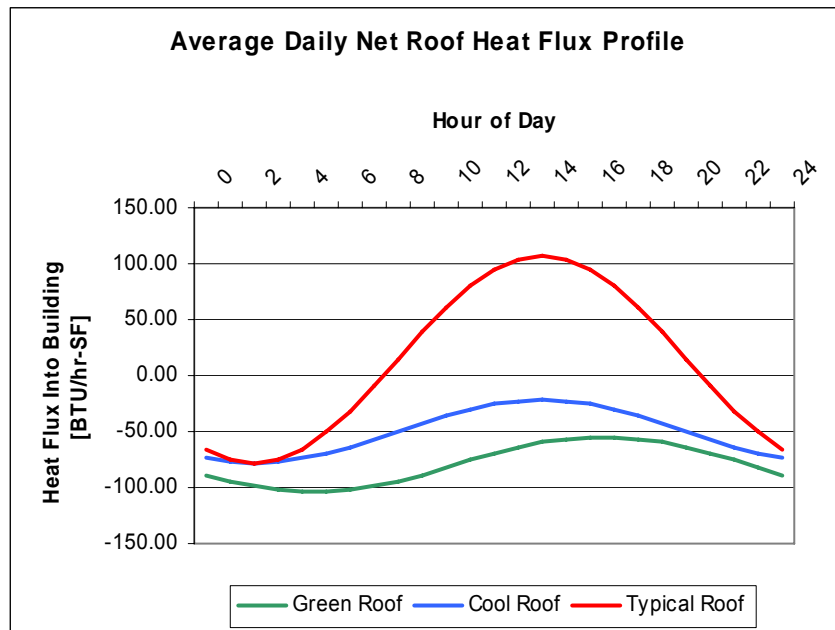Figure 6.9: Average net heat flux into SLCC per hour.

Figure 6.10: Average net heat gain histogram through different roof types.

6.4.2. CONCLUSIONS

The annual average net heat gains and associated cooling costs/savings for each roof type are described in Table 6.3. Based on the cost of remote chilled water production for the facility ($0.026495/MBH), the green roof produces significant savings in annual energy use over the budget model. However, compared to the actual design of the SLCC cool roof, the green roof does not produce significant savings (Table 6.3). This, of course, is for the ideal conditions of each roof. Given that the cool roof is likely to lose some of its reflectivity over its life (let's assume $\alpha = 0.5$ sometime in the future), green roof energy savings over the cool roof may double to over $14,000/yr.

Total Energy Savings for Green Roof Design

	Green Roof			Cool Roof	Typical Roof
	Cooling Load [BTU/hr-ft^2]	Savings [MBH/hr]	Savings [$]	Cooling Load [BTU/hr]	Cooling Load [BTU/hr]
Average 24hr	79.09	723	$0.02	49.83	
		4,236	$0.11		92.35
Annual	28,887	264,110	**$6,997.60**	18,199	
		1,547,283	**$40,995.27**		33,730

Green Roof Area: 24710ft^2

Table 6.3: Total energy costs savings for green roof compared to cool roof, typical roof.

6.5. STORMWATER RETENTION

A primary benefit of green roofs is their ability to manage stormwater. Precipitation is captured and stored rather than being shed. An extensive green roof has the capability of retaining about 70% of precipitation and acts as a natural filter. Also, a green roof acts as a capacitor in that it holds water back from the storm sewer system and discharges it at a later time and at a slower rate. A traditional roof, however, immediately sheds approximately 95% of precipitation upon it. As a result, the load on the storm sewer infrastructure is reduced which has a direct impact on flash flooding (LEED).

Also, the runoff of pollution and sediment is minimized. Water that is filtered through the soil substrate experiences bioremediation and photoremediation which remove pollution. This is critical for the health of the waterways downstream. The SLCC is located within the Anacostia Watershed (

Figure 6.11). This river has a history of pollution and is a part of the sensitive Chesapeake Bay Watershed. Controlling stormwater runoff and along with it pollution and sediment is critical to the survival of these habitats (Anacostia Watershed Society).

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Figure 6.11: The SLCC (red dot) is located in the Anacostia Watershed (yellow).

An analysis of impervious area and stormwater runoff is included in the LEED Sustainable Sites Credits. The goal is to reduce the amount of impervious area on the building site from pre-construction to post-construction. The site of the SLCC originally consisted of an asphalt parking lot and grass/dirt lawn. The current design for the site (
Figure 6.12) increases the amount of impervious surface area because of the impervious footprint of the building.
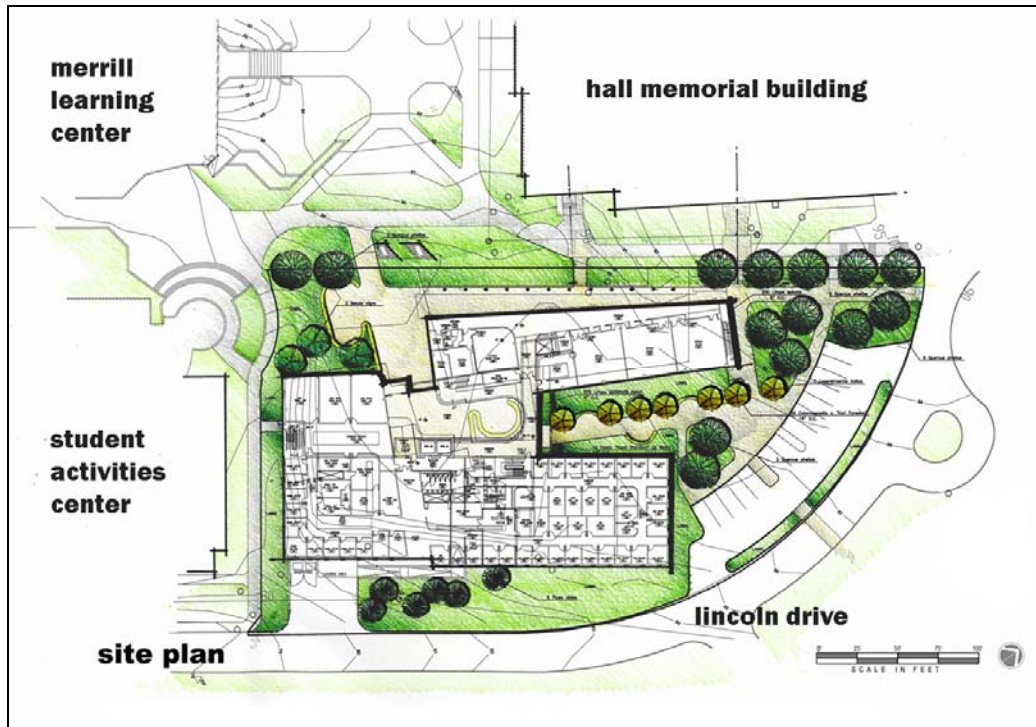

Figure 6.12: Site plan for the SLCC.

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The addition of a green roof, however, greatly reduces this impervious area. Table 6.4 shows a comparison of the amount of impervious area on the site before and after construction for each design. The proposed green roof alone reduces stormwater runoff by 5% compared to the pre-construction site and reduces runoff by 25% compared to the actual site design. The amount of runoff from the actual SLCC site design per year is equivalent to 75% of the atrium volume.

Annual Site Stormwater Runoff

	Runoff Coefficient	Original Site			Actual Design			Proposed Green Roof Design		
		Area [SF]	% of Site	Runoff [CF]	Area [SF]	% of Site	Runoff [CF]	Area [SF]	% of Total	Runoff [CF]
Asphalt/Concrete:	0.95	42550	54.8%	130127	30360	39.1%	92847	30360	39.1%	92847
Building (roof):	0.95	0	0.0%	0	33840	43.6%	103490	9130	11.8%	27921
Grass:	0.25	28050	36.1%	22574	13400	17.3%	10784	13400	17.3%	10784
Green Roof:	0.30	0	0.0%	0	0	0.0%	0	24710	31.8%	23864
Other:	0.50	7000	9.0%	11267	0	0.0%	0	0	0.0%	0
Total Pervious:	0.00	26665	34.4%	0	13260	17.1%	0	29322	37.8%	0
Total Impervious:	1.00	50935	65.6%	163968	64340	82.9%	207121	48279	62.2%	155417
TOTAL		77600		163968	77600		207121	77600		155417

Site Area [SF]: 77600
Annual Precip. [in]: 38.63

Table 6.4: Annual site stormwater runoff.

If pervious pavement is used in the parking lot rather than asphalt another 33,000CF of rain water is retained on the site (Table 6.5). The impervious area of the new site would be 25.3% less than the undeveloped site.

Annual Site Stormwater Runoff

	Runoff Coefficient	Original Site		Green Roof, Perv. Parking		
		Area [SF]	Runoff [CF]	Area [SF]	% of Total	Runoff [CF]
Asphalt/Concrete:	0.95	42550	130127	22260	28.7%	68076
Pervious Concrete	0.60	0	0	8100	10.4%	15645
Building (roof):	0.95	0	0	9130	11.8%	27921
Grass:	0.25	28050	22574	13400	17.3%	10784
Green Roof:	0.00	0	0	24710	31.8%	0
Other:	0.50	7000	11267	0	0.0%	0
Total Pervious:	0.00	26665	0	44430	57.3%	0
Total Impervious:	1.00	50935	163968	33171	42.7%	106781
TOTAL		77600	163968	77600		122427

Site Area [SF]: 77600
Annual Precip. [in]: 38.63

Table 6.5: Annual stormwater runoff with green roof and pervious pavement.

Another advantage of the green roof stormwater retention is the ability to downsize roof downspouts. Since the soil and plant material hold back about 70% of rainfall the amount of water drained from the roof is dramatically less. The original roof design uses 6in. downspouts for all roof drainage areas. Some of these are oversized, but all are likely the same size for uniformity. The calculations below show the sizing of the downspouts for two (2) areas of the original roof and green roof (Figure 6.13) based on rainfall of 3.2in./hr. during a one hour storm for a 100 year return period in Washington, DC (MIFAB) (International Plumbing Code Table 1106.6).
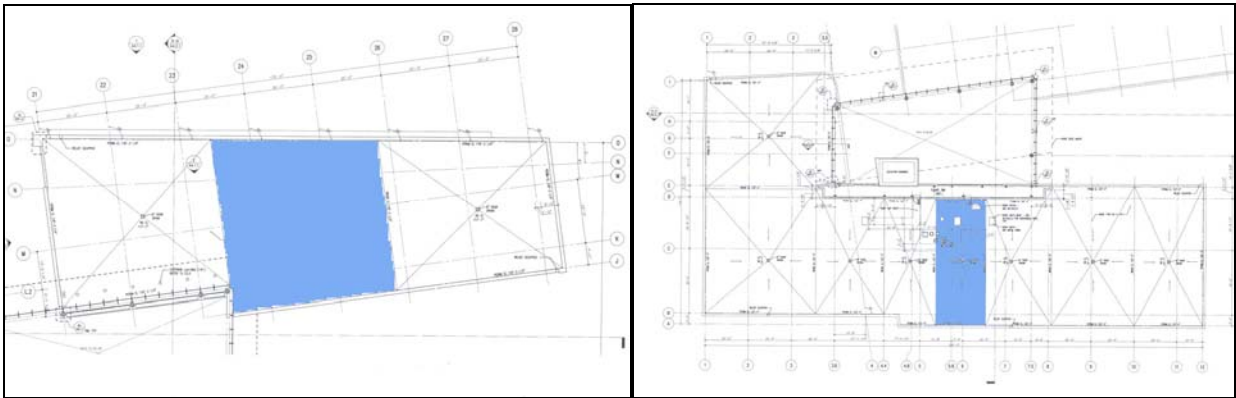

Figure 6.13: Roof drainage areas 1 (left) and 2 (right).

Drainage area of roof:

$$A_1 = (58\text{ft})*(66\text{ft}) = 3{,}828 \text{ ft}^2$$
$$A_2 = (20\text{ft})*(60\text{ft}) = 1{,}200 \text{ ft}^2$$

Runoff per hour:

$$V_{1,\text{ original roof}} = (3{,}828 \text{ ft}^2)*(3.2\text{in/hr})*(0.0104 \text{ gpm/in-ft}^2) = 127.4 \text{ gpm/hr}$$
$$V_{1,\text{green roof}} = (3{,}828 \text{ ft}^2)*(3.2\text{in/hr})*(0.3)*(0.0104 \text{ gpm/in-ft}^2) = 38.2 \text{ gpm/hr}$$

$$V_{2,\text{ original roof}} = (1{,}200 \text{ ft}^2)*(3.2\text{in/hr})*(0.0104 \text{ gpm/in-ft}^2) = 40.0 \text{ gpm/hr}$$
$$V_{2,\text{green roof}} = (1{,}200 \text{ ft}^2)*(3.2\text{in/hr})*(0.3)*(0.0104 \text{ gpm/in-ft}^2) = 12.0 \text{ gpm/hr}$$

Roof Downspout Sizing			
Roof Area	Roof Type	Design DS Size (in. dia.)	Actual DS Size (in. dia.)
1	Original	6	6
	Green	4	4
2	Original	3	6
	Green	2	4

Table 6.6: Roof downspout sizes.

6.6.   URBAN HEAT ISLAND EFFECT

Green roofs also have the ability to reduce the urban heat island effect. This phenomenon is defined in the LEED v2.1 Reference Guide as the occurrence of "warmer temperatures in an urban landscape compared to adjacent rural areas as a result of solar energy retention on constructed surfaces" such as parking lots, streets, sidewalks, and buildings. Vegetation tends to cool surrounding areas by shading and evapotranspiration whereas the built environment tends to absorb solar radiation and radiate it back to the surroundings. The result is an increase in urban temperatures of up to 10°F when compared to surrounding areas. This impacts the building cooling loads by increasing heat loss through the envelope and thus requires larger mechanical equipment and energy use.

Washington, DC is subject to this urban heat island effect. Figure 6.14 depicts the range of infrared radiation from surfaces in the metro area of Washington, DC. Blue indicates buildings, streets, parking lots, etc that re-radiate this energy to the surroundings and thus increase ambient temperatures. Red areas show vegetation (the National Mall can easily be seen in the center of the image) that do not radiate as much energy (Baumann). The proposed SLCC green roof (and original cool roof) would act to decrease the "blue" area of the city.

Low Thermal Radiation (vegetation)   High Thermal Radiation (buildings)
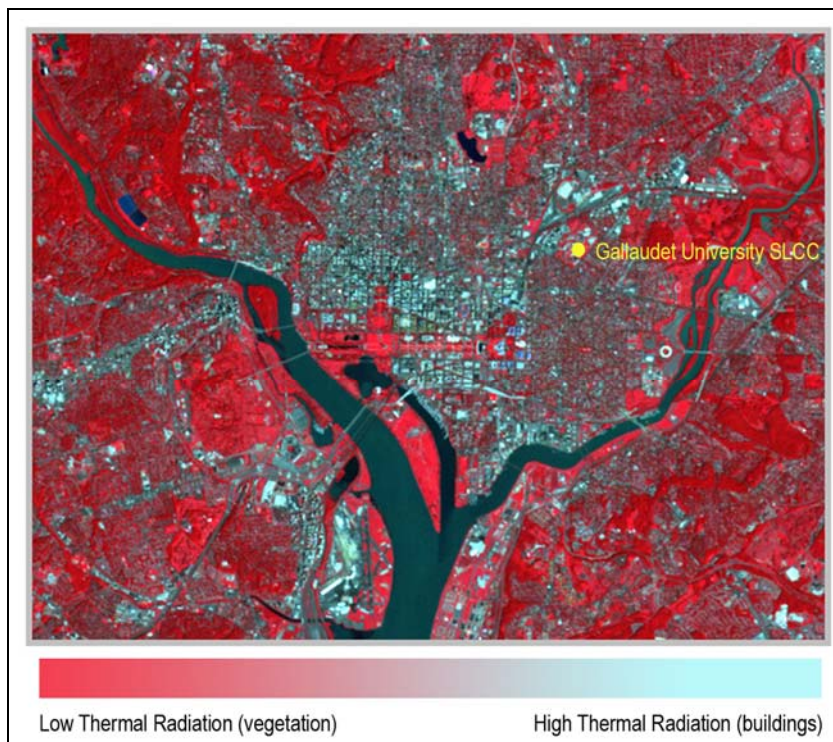
Figure 6.14: Thermal radiation in the urban Washington, DC environment in 1990(Baumann).