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ARTICLE

Laboratory and Mathematical Modeling of Green Roof and Different Color Roofs

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ABSTRACT

Several studies were compiled using data from physical models of green and black surfaces in the lab and the Cooper Union (CU) roof as well as green roof studies of the Javits Green Roof (JGR) measured over a six-year period. Observations were made with weather stations, custom designed draining systems and three partial flumes each equipped with a pressure transducer and weighing lysimeters. An infrared camera was used at the CU and JGR to collect thermal images to determine the effectiveness these roofs had for thermal buffering. A multiple regression curve was calculated relating the lysimeter mass and five independent variables, with the precipitation runoff and retention time being the most important variables. The surface of the black roof was compared to white and green roofs at CU. The temperature was significantly higher (over 70 °C) on the black roof clearly showing the advantage of using a green roof. The ET was calculated on the JGR using the Penman-Monteith (P/M) equations. The runoff hydrograph for the JGR was constant with an increase in precipitation and storage when the hydrograph dropped in response to the precipitation and storage. When the plots (185 square meters at JGR) were irrigated, the dry plots always had higher temperatures (above 15 °C during summer daytime). The ET is the controlling factor for temperature reduction on a vegetated green roof as shown in the JGR data. The relative humidity (RH) was measured in the CU lab and on the JGR and showed similar results. The RH dropped during higher temperatures and recovered at lower temperatures. The results of these studies at CU and JGR clearly show the benefits of using a vegetated green roof.

Keywords: Green roof; Black roof; PM equation; ET

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1. Introduction

The world is currently entering a period of rapid and significant change. The past five years alone have been the hottest five years recorded since major weather and climate agencies began to track global temperatures in the 1880's. July 2023 has been the hottest month ever recorded in history [1]. Scientists estimate that by 2100, the average global temperature will increase by at least 3.5 °C [2]. In the past 141 years, the average global temperature increased by 1 °C [3].

The consequences of these climatic shifts are profound and far-reaching. As global temperatures continue to rise, the frequency and intensity of extreme weather events are on the rise. Notably, the increasing number of hurricanes, wildfires, and heatwaves are wreaking havoc on ecosystems, communities, and economies around the world. Coastal regions are particularly vulnerable, with rising sea levels and more frequent hurricanes threatening the very existence of certain areas [4]. The Mississippi River Delta, once a thriving and ecologically diverse region, now faces the double threat of subsidence and sea level rise, putting its unique ecosystem at risk. Simultaneously, the eastern coast of the United States is grappling with the peril of increased flooding due to sea-level rise. As sea levels continue to surge, urban areas are becoming more susceptible to inundation, jeopardizing the livelihoods of countless residents [5].

Beyond North America, the repercussions of climate change are global in scale. The Arctic permafrost, a region that has remained frozen for millennia, is beginning to thaw due to extended periods of warming and longer summers in Alaska [6]. This thawing has dire implications, as it can lead to the release of potent greenhouse gases like methane, further exacerbating global warming. In more distant regions like the Amazon rainforest, a symbol of natural beauty and biodiversity, the delicate balance of life is threatened. The rainforest, which has stood for ten million years, now faces an uncertain future as deforestation, droughts, and fires become increasingly prevalent. These environmental transformations underscore the urgency of addressing climate change and its impacts, not only for the environment but also for the well-being of future generations [4].

One form of green infrastructure is the green roof. Green roofs are multi-level roofing layers on buildings, coated with vegetation [7]. Research concerning the thermal performance of green roofs in urban and suburban settings is new. The majority of this work emphasizes the thermal benefits of green roofs over traditional black tar asphalt and gravel roofs. Green roofs provide physical protection of the conventional roof from solar radiation and reduce both daily and seasonal variations in surface temperature. This buffering is accomplished through reflection, convection, vaporization, and eventual transmission processes. Green roofs typically have a higher albedo than traditional black roofs, and thus are able to reflect a larger fraction of the incident solar radiation away from the roof surface. Radiation that is not reflected away from the surface heats up the green roof elements (vegetation, growing media, and the moisture stored within it) rather than the roof [8].

The goals of this paper are to prevent long-term, rainfall-runoff observations from three 186 m^2 drainage areas or plots of the Jacobs green roof in New York City (NYC). The study is novel because it is situated in New York City, whose $1.4 billion plan aims to capture 25 mm of precipitation over 10% of the city's impervious surfaces using various forms of green infrastructure, including green roofs. As opportunities for street level green infrastructure implementation are rapidly diminishing, the city is looking for new opportunities to manage storm water on its' over 56 million square meters of rooftops. It has been estimated that greening all rooftop spaces in NYC would result in an average of 1.6 °C reduction in temperature, a 38-billion reduction in annual storm water flow and energy cost savings amounting to roughly $130 million annually. Research documenting the hydrologic benefits of green roofs in NYC's unique urban climate is a first step towards evaluating whether such goals are achievable, with municipal funds dedicated to wet weather management [9,10].

Results show that overhead irrigation was the most favorable for plant growth and health. Since green roof substrates tend to be coarse to allow adequate drainage, water does not move laterally to a great extent as it would in finer substrates. For this reason, drip and sub irrigation may not be the most efficient irrigation methods. Moore et al. [10] concluded overhead irrigation may be a better choice, as it distributes water more uniformly and leads to higher substrate water holding capacity (WHC), less runoff, and better plant growth and health compared to drip irrigation. Another strategy to adapt to the irrigation requirement is by optimal design of green roof materials, such as developing green roof substrates with higher WHC [11]. The addition of sandy loam soil and the use of amended soils (i.e., mix of red gravel, vermiculite and bark compost), perlite-based substrates, foam sheets and fiberglass can all improve the WHC of the green roof system. Some water holding additives, like hydrophilic gels, are also currently being explored. A second way to conserve water is by finding alternative irrigation sources. For example, gray water, which is the wastewater from in and around the house (including bathroom sinks, showers and washing machines, but excluding water originating from toilet flushing, dishwashers and kitchen sinks), could be reused for irrigation purposes [12]. Another possibility is rainwater harvesting in which runoff is collected and stored. Runoff harvested from green roofs themselves has been shown to be sufficiently clean enough to be reused for urban irrigation. In the third category, irrigation quantity can be minimized through monitoring and control of irrigation regimes [13]. Meteorological factors, mainly relative humidity and number of sunshine hours as they affect water consumption the most, are important to consider for green roof irrigation systems. Otherwise, irrigation should be turned on when the substrate moisture drops below a specified level, like the stress point (transition between readily available water in the substrates larger pores and less available water in the small pores). Irrigation can be controlled using a smart controller, which turns on when necessary (at night or when soil moisture is below the stress point) but deactivated when rainfall is registered.

During the establishment phase and the first growing season throughout the summer, it is advised to use irrigation on all green roof types and climates. Afterwards, irrigation is only necessary on extensive green roofs in arid climates and temperature climates with dry periods. In this study on JGR, two methods of irrigation were studied: overhead sprinklers and dry irrigation (half inch tubes with small holes every 18 inches). There were two sets of roof plots, one being wet irrigation and the second with no irrigation. Both plots were monitored with temperature and humidity probes. The intake air temperatures on four RTUs were also determined. The ceiling temperatures were also measured under the dry and wet plots. The energy consumed by the center was determined for the irrigation activities and savings in cost.

A mathematical model is presented to compare the results of thermal buffering to a 2018 model using the error function. There was a good correlation found between these two models. Eumorfopoulou and Aravanteous [14] calculation has been completed using the stationary method in order to determine the thermal behavior of the planted roof and the way it influences the thermal protection of buildings in accordance with Greek climate conditions. They reduce solar radiation, daily thermal variations and annual thermal fluctuations.

2. Materials and methods

The Jacob Javits Convention Center's extensive green roof was completed in the spring of 2014 stretching 27,316 m^2 across two roof sections. The Javits Green Roof (JGR) consists of the XERO Flor XF301 + XT extensive green roof system. In this section, the design consists of a pre-vegetated sedum mat installed on top of 1.5 to 5 mm of growing medium, a retention fleece layer, a drainage layer, and a root barrier. The XF301 pre-vegetated sedum mat is obtained from various nursery farms in upstate New York in the mid-Atlantic (South Carolina) and the mid-west United States. The sedum mat is an integrated unit of plant materials and growing medium meshed onto a geotextile which combines these components together. The XeroTerr growing medium is a mix of a lightweight mineral aggregate and organic matter designed to provide the sedum with all the nutrition needed to fully mature. The XF157 water retention fleece is a fabric comprised of recycled fiber materials that provides a robust layer for plant roots to latch on and grow. The fleece also serves as a filter layer to screen water that may carry minerals from the growing medium layer or from the precipitation. The XF108H drain mat is a geotextile layer attached to a mesh of polymeric fibers (2 mm thick) designed to create a clear space for excess water to drain out from the topmost layers. Finally, the XF112 root barrier is a near water-impermeable layer designed to deter the plant roots from establishing themselves any further down into the actual roof structure [9,15].

Campbell Scientific weather stations were installed on the JGR shortly after the start of construction to collect meteorological data during and after construction. The weather stations log data at five-minute intervals onto a Campbell Scientific CR1000 logger. Four stations were set up each equipped with a Texas Electronics, Inc. Series 525—Rainfall Sensor and additional monitoring sensors for temperature and net-radiation. The Campbell Scientific data logger uploads the recorded data in real time onto a VistaDV online application managed by the Sustainable Water Resource Engineering Laboratory at Drexel University. Additional monitoring instruments included: Parshall flumes, weighing lysimeters, soil sensors, and a mobile infrared camera. The three plots from which runoff is monitored each have a tributary drainage area of 186 m^2 and each discharge to a single roof drain. These plots are hereinafter referred to as Station 4, Station 5 and Station 6.

Although precipitation data was collected at three locations, the rain data from three weather stations is used in this study as the primary source of data for calculating total precipitation volume, water (**Table 1**) retention/detention, and storm characteristics (storm duration, intensity, and antecedent dry period) of rain events and its effect on the JGR response. A 2-hour period is used as the minimum time between rain events to separate individual storms. The rain events are, in turn, classified into three different categories based on the total quantity of recorded rainfall: low rainfall (< 6.25 mm), medium rainfall (6.35 to 12.7 mm) and heavy rainfall (> 12.7 mm).

Table 1. Locations on the JGR.

ID#	Description	Weather station	Weighing lysimeter	Soil sensors (lysimeter)	Soil sensors (transect)	Parshall flume
1	Roof of the link building	1				
2	Light pole of 11th avenue	1				
3	North green roof	1				
4	South green roof—plot a		1	2	3	1
5	South green roof—plot b		1	2	3	1
6	South green roof—plot c	1	1	2	3	1
	Total	**4**	**3**	**6**	**9**	**3**

3. Results

Figure 1 shows the green (grass) and black boxes that represent the green and black roofs measured in CU labs [16,17]. The IR photograph has red surfaces with average surface temperatures of 22.7 °C and green surfaces with average temperatures of 19.5 °C. The peak histography polygon black surface has a value approaching 940 and the green surface has a value of 350. The histography polygon for both surfaces shows a Gaussian distribution with a widespread for the green roof hot spots max temperature approaching the black surface. The experiment shows similar values in **Figure 1** again with a widespread for the green roof temps. Average differences between the two surfaces can exceed 15 °C. The IR photos (**Figure 1**) of the surfaces have black box temperatures approaching 24 °C and average green surface temperatures of 18 °C. **Figure 2** below shows a graph of the temperature variation for black, white, and green surfaces (measured on the CU roof) over a 10-hour period [18,19].

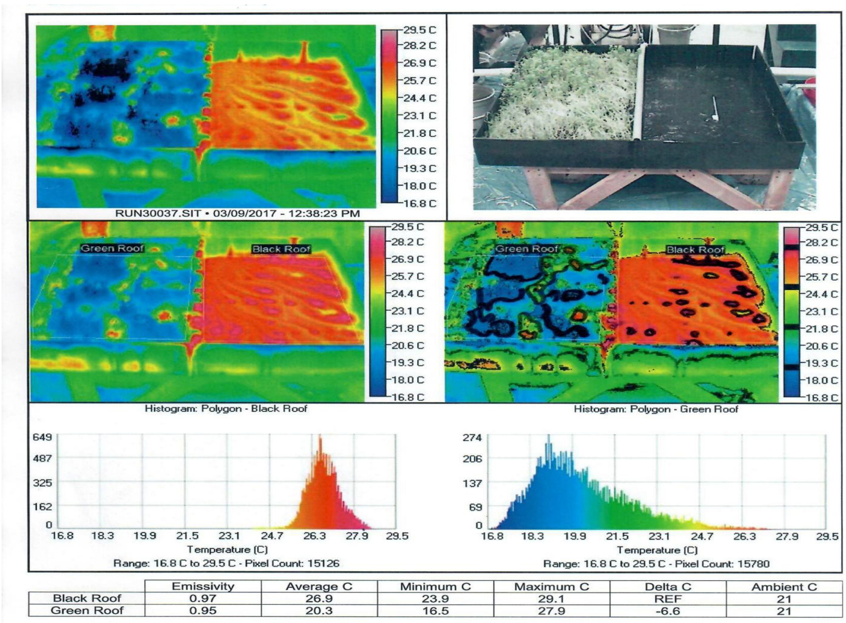

Figure 1. Thermographic report for cooper union green roof study.

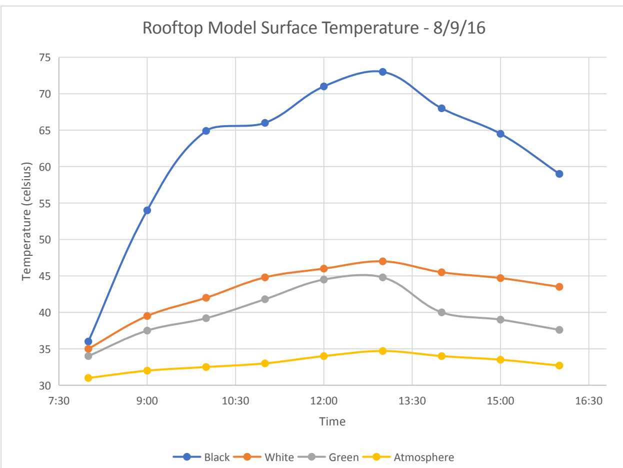

Figure 2. Rooftop model surface temperature.

The black surface temperatures exceed over 70 °C at 1 p.m. There is over a 25 °C difference in temperature between the black and white surface with the green surface about 2 to 5 °C lower than the white surface. The air temperature for this time period was less than 35 °C. During the period (12:00–13:30) it was difficult to place your hand on the black surface. The white and green surfaces were cool in comparison. **Figure 3** below shows a graph of the black and green surface temperatures at different times and vertical distances from the surfaces. The black surface has temperatures exceeding 60 °C for over 4 hours at 14 cm from the surface [14] with surface temperatures over 65 °C. Again, in comparison, the green surface temperatures are always below 45 °C. For these data sets, the ambient air temperatures are below 33 °C. The white surface temperatures have a similar temperature distribution to that of the green surface but about 2–9 °C warmer shown in **Figure 3** measured on 7/20/16 at 1 p.m. All these surface temperatures approach the air temperature of 34 °C, 45 cm from the surface. The black surface shows extreme surface temperatures that are difficult to be adjacent to. The green roof was replaced with an earth roof (the same used on Javits roof) and the temperature study was repeated. The temperatures on the earth roof range from 2 to 9 °C higher than the white roof. At 20 cm above the surface, the temperature was the same as ambient air [20].

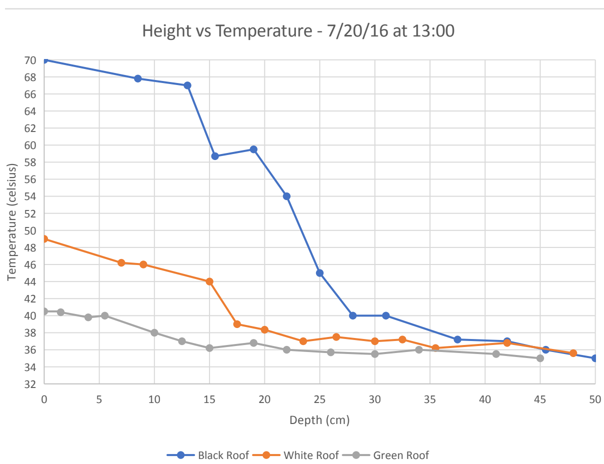

Figure 3. Rooftop model surface temperature.

A temperature run was conducted during the cold weather (12/28/16) at JGR. The air temperature levels out to about 4 °C with the indoor ceiling and floor temperature within 1 °C (floor temperature higher). The surface temperatures of the roof and street on 11th avenue were within 1 °C and average differences above 4 °C from 9 a.m.–3 p.m. [21]. A graph of the relative humidity (RH) is given in **Figure 4** showing the change in RH for a blank surface measured in the lab for six different heights. When the heat lab was turned on at 10:40 a.m., the RH on the surface dropped and recovered to 45% when the heat lamp was turned off at 11:20. The RH is higher at a larger vertical distance from the surface. White and green surfaces had the same shape and magnitude for RH, measured at three locations at the 11th avenue weather station. There was rain on 7/18 and no rain until 7/22. Note, the high value of RH on 7/18 and leveling off until the next rain period after the last measurement of RH on 7/22 [11,12,22].

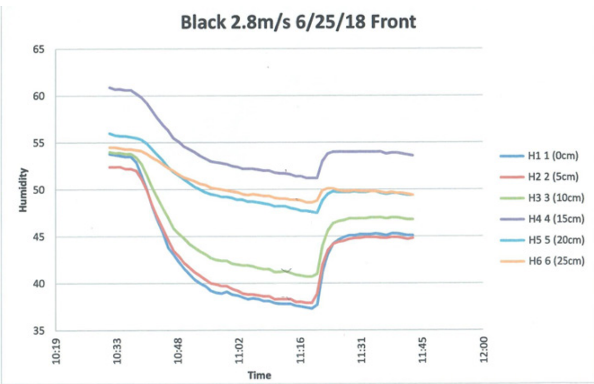

Figure 4. Humidity on black surface.

The RH for the Javits center drops from over 97% to about 80% to a low of about 40%. For all of the four locations, the RH is the same. The peak RH is at about 6 a.m. and low about 6 p.m. The air temperature averages about approximately 33 °C during this time. **Figure 4** shows a double-peaked hydrograph for two different Javits roof plots (flumes 4 and 5) both 45 by 90 feet [15]. Note, this double-peaked hydrograph is in response to changes in precipitation the shape and magnitude of these two hydrographs are the same. The 2ft-by-2ft lysimeter graph is also shown in **Figure 5** below in pounds. Note this is a relative graph starting at about 87 pounds and leveling at 88 pounds. There is a rapid response to the storage and small drainage [23] (about ½ pound) before a value of about 88 pounds. Most of the hydrographs showed single peaks with the same hydrographs for flumes 4 and 5.

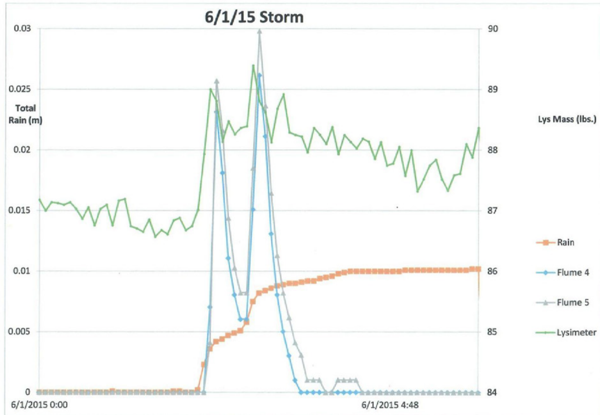

Figure 5. Hydrograph, lysimeter and rain total during 6/1/15 storm.

The ambient air temperature has a maximum of about 27 °C at 15:00 with the concrete walkway maximum of about 33 °C the grass maximum of about 32 °C with the max temperature of the grass near the RTU close to the concrete walkway [24].

Figure 6 below shows the temperature variation at the RTU with white tape and gray air temperature, net and total radiation. The temperature and radiation have the same outline as the air temperature [25].

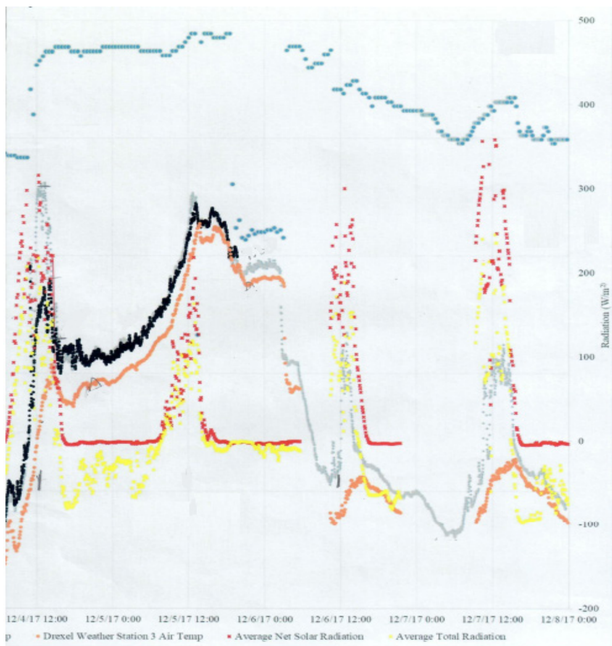

Figure 6. Surface temperatures, net radiation and average total radiation.

The Javits roof was irrigated at different sections (wet) & compacted to dry sections of the green roof. **Figure 7** (7/18 to 7/30) shows sections of the wet and dry roof. The dry plot temperature is about 15 °C higher than the wet plot. There is also a larger variation for the dry between a.m. and p.m. The RH has an inverse variation compared to the air temperature; the larger air temperature corresponds to a low RH. The soil moisture values are similar comparing the wet and dry across the green roof with values [26] between 0.4 to 0.15 m^3/m^3 [27].

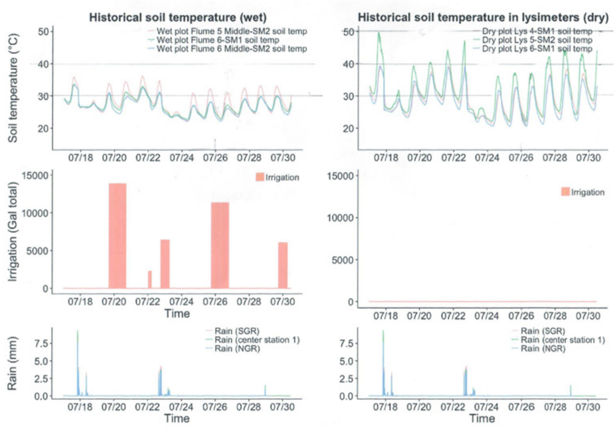

Figure 7. Soil temperatures, irrigation, rain vs time from 7/18 to 7/30.

4. Discussion

A multiple regression curve was calculated using a lysimeter mass as the dependent variable and the precipitation time, runoff, retention time, antecedent time and detention time as the independent variable. See reference Alvizuri 2018 for a relation between lysimeter mass and antecedent time. The adjusted R squared is the value to use when analyzing multiple independent values. For this analysis, 84.2% of the points fall on the regression line. The coefficient of the intercepts is used to write the equations of the regression line. For this analysis, the equation is:

$$y = 1.557x_1 - 1.5016x_2 - 0.74x_3 + 0.000007x_4 - 0.0037x_5$$

where y is the change in lysimeter mass, x_1 precipitation, x_2 runoff, x_3 retention time, x_4 antecedent time and x_5 detention time. The temperatures measured on the black, white and green roof surface on the CU roof clearly showed excessively high temperature on the black surface with values about 50 °C higher than the air temp. At 72 °C the black roof was uncomfortable to the touch. In comparison, the white and green roofs were less than 47 °C and felt relatively cool. Evaporation and transpiration combined is called evapotranspiration (ET) and is the largest component of losses in rainfall-runoff sequences. The ET measurements are an indication of the values of roof temperatures. Penman in 1948 related ET to meteorological variables, combining the energy balance required to sustain evaporation with the mechanism required to remove water vapor. This equation allows ET to be measured in terms of energy and is shown as the "Penman-Monteith method" [18]. The value of ET has been calculated for a set of measured meteorological conditions for the Javits green roof and is tabulated. The P/M equation includes latent heat flux. An Excel spreadsheet was set up to calculate the ET every five minutes and is shown. For this set of inputs ET was 2.6 mm/d. A survey on the Javits (11/30/17 to 12/8/17) roof shows a correlation between the air temperature, RTU intake and discharge temperature and radiation. By observing the CU roof temperature with black surface and the Javits roof temperature, it is clear that the green roof moderates the temperature and that the black roofs are the worst case for roofs. The black surface absorbs heat with surface temperatures over 70 °C where the green roof surface temperature is close to the air temperature (**Figure 7**) even with the net radiation peaking a little past noon.

The average daily AET value measured on the Javits green roof between the summer months of June and July 2017 was 2.6 mm/d (1.2 mm/d). This evaporation intensity can be expressed in power units, considering the conservation of water from liquid to about 2,000 BTU for each kilogram of liquid water and assuming a constant density of water 1000 kg/m^3. The solar power required to drive the mean rooftop ET is thus equivalent to 2717.7 BTU per day per square meter of roof a 3.1 × 106 BTU/hr over the entire roof. For comparison, an average studio apartment in NYC is approximately 51 m^2 (550 ft^2) in size and requires an air conditioning unit with 14,000 BTU/hr cooling capacity. The solar power consumed in evaporating water of the

Javits green roof is thus equivalent to the power requirement to cool 220 NYC studio apartments with air conditioning.

The double peak hydrograph, cumulative precipitation, and storage on the Javits roof are consistent, i.e., as precipitation increased the outflow measured in flumes 4 & 5 increased and the drop in the hydrographs are responses to the drop in precipitation. The storage also reacts to these changes by showing an increase and then leveling off. The storage has a small drainage (about ½ lb) before leveling at about 88 lbs. Results of an irrigation study [28] comparing wet plots on the Javits roof to dry plots were conducted and recorded from 7/18 to 7/30 (**Figure 7**). The dry plot temperature where higher than the wet plots by over 15 °C. The ET is about 3% of the water balance (2018) but leads to lowering the temperature in the green roof. Clearly, ET is one of the controlling features in lowering and controlling heat on a vegetative roof. Repeated experiments on the CU lab and roof and JCC green roof indicate the effect of this mechanism as well as the albite, color of the roof (black versus white). The soil temperature in a wet plot was always lower than in a dry plot (**Figure 7**).

The RH was measured under heat lamp for black and white surfaces in the CU lab. As the heat lamp was turned on, the RH dropped from about 53 to 32 as to be expected and recovered when the heat lamp was turned off. There was little difference between the black and white surfaces. The variation of RH on the Javits green roof showed similar variation again showing lower values at higher ambient temperatures.

5. Conclusions

Multiple regression curves were calculated relating the change in lysimeter mass to five independent variables with the precipitation, runoff, and retention time being the most important. The coefficient of regression (R squared) values was always greater than 84% showing a strong correlation to the Javits roof storage and the five dependent variables. The surface of the roof at CU was black and significantly higher (70 °C) compared to the white and green roof. At 72 °C the black roof was uncomfortable to touch but the white and green roofs were less than 47 °C and were relatively cool. The ET is a measure of the roof to control their surface temp. The ET is the largest component of losses rainfall-runoff sequences change. The P/M equations were used to predict the ET on the Javits green roof with a value of ET 2.6 mm/d. The P/M equation includes all of the meteorological measurements on the Javits weather stations (2018). An Excel spreadsheet was set up to calculate the ET every five minutes. From the CU roof study of surfaces, black is the worst color for temperature moderation while the green irrigated roof clearly moderates the soil temperature. The green roof surface is close to the ambient air temperature measured on the Javits green roof. The hydrograph measured on the JGR shows a correlation between the runoff from the two plots and the precipitation and lysimeters storage. The increases and drops in hydrograph match the precipitation accumulation and lysimeters storage and the lysimeters leveling off as the precipitation drops. When the 185 square meter plots are irrigated, the wet green roof soil is always lower temperature wise than the dry soil by as much as 15 °C during summer months. The soil temperature, TR intakes and discharge RTU temperature all peaked at about noon.

The RH was measured under the heat lamp for the black and white surface in the CU lab. As the heat lamp was turned on, the RH drop was to be expected and recovered when the heat lamp was turned off. There was little difference between the black and white surface. The variation of RH on the Javits green Roof showed similar variation again lowering values at higher ambient temperatures.

Author Contributions

Joseph Cataldo: Abstract, Introduction, Discussion, Results and conclusions.Yara Elborolosy: Methods, Results and Conclusions.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

All data can be provided upon request.

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References

[1] Wang, L., Wang, L., Li, Y., et al., 2023. A century-long analysis of global warming and earth temperature using a random walk with drift approach. Decision Analytics Journal. 7, 100237. DOI: https://doi.org/10.1016/j.dajour.2023.100237

[2] Santos, F.D., Ferreira, P.L., Pedersen, J.S.T., 2022. The climate change challenge: A review of the barriers and solutions to deliver a Paris solution. Climate. 10(5), 75. DOI: https://doi.org/10.3390/cli10050075

[3] Mayo, A.L., Lin, N., 2022. Climate change impacts to the coastal flood hazard in the northeastern United States. Weather and Climate Extremes. 36, 100453. DOI: https://doi.org/10.1016/j.wace.2022.100453

[4] Ebi, K.L., Vanos, J., Baldwin, J.W., et al., 2021. Extreme weather and climate change: Population health and health system implications. Annual Review of Public Health. 42, 293–315. DOI: https://doi.org/10.1146/annurev-publhealth-012420-105026

[5] Reed, T., Mason, L.R., Ekenga, C.C., 2020. Adapting to climate change in the upper Mississippi River Basin: Exploring stakeholder perspectives on river system management and flood risk reduction. Environmental Health Insights. 14. DOI: https://doi.org/10.1177/1178630220984153

[6] Jin, X.Y., Jin, H.J., Iwahana, G., et al., 2021. Impacts of climate-induced permafrost degradation on vegetation: A review. Advances in Climate Change Research. 12(1), 29–47. DOI: https://doi.org/10.1016/j.accre.2020.07.002

[7] Shahmohammad, M., Hosseinzadeh, M., Dvorak, B., et al., 2022. Sustainable green roofs: A comprehensive review of influential factors. Environmental Science and Pollution Research. 29, 78228–78254. DOI: https://doi.org/10.1007/s11356-022-23405-x

[8] Schade, J., Lidelöw, S., Lönnqvist, J., 2021. The thermal performance of a green roof on a highly insulated building in a sub-arctic climate. Energy and Buildings. 241, 110961. DOI: https://doi.org/10.1016/j.enbuild.2021.110961

[9] Alvizuri, J., Cataldo, J., Smalls-Mantey, L.A., et al., 2017. Green roof thermal buffering: Insights derived from fixed and portable monitoring equipment. Energy and Buildings. 151, 455–468. DOI: https://doi.org/10.1016/j.enbuild.2017.06.020

[10] Moore, J.C., Leib, B., Hansen, Z.R., et al., 2022. Comparing overhead versus drip irrigation for production of three cultivars of romaine lettuce on biodegradable plastic mulch. HortTechnology. 32(1), 39–46. DOI: https://doi.org/10.21273/HORTTECH04916-21

[11] Vanuytrecht, E., Van Mechelen, C., Van Meerbeek, K., et al., 2014. Runoff and vegetation stress of green roofs under different climate change scenarios. Landscape and Urban Planning. 122, 68–77. DOI: https://doi.org/10.1016/j.landurbplan.2013.11.001

[12] Silva, J.R.M., Celeri, M.O., Borges, A.C., et al., 2023. Greywater as a water resource in agriculture: The acceptance and perception from Brazilian agricultural technicians. Agricultural Water Management. 280, 108227. DOI: https://doi.org/10.1016/j.agwat.2023.108227

[13] Raimondi, A., Quinn, R., Abhijith, G.R., et al., 2023. Rainwater harvesting and treatment: State of the art and perspectives. Water. 15(8), 1518. DOI: https://doi.org/10.3390/w15081518

[14] Eumorfopoulou, E., Aravantinos, D., 1998. The contribution of a planted roof to the thermal protection of buildings in Greece. Energy and Buildings. 27(1), 29–36.

DOI: https://doi.org/10.1016/S0378-7788(97)00023-6

[15] Abualfaraj, N., Cataldo, J., Elborolosy, Y., et al., 2018. Monitoring and modeling the long-term rainfall-runoff response of the Jacob K. Javits Center green roof. Water. 10(11), 1494. DOI: https://doi.org/10.3390/w10111494

[16] Sanyal, H., Cataldo, J., 2022. Laboratory experiments and modelling to determine the profiles of the Javits Center Green Roof. International Journal of Environmental Impacts. 5(4), 350–361. DOI: https://doi.org/10.2495/EI-V5-N4-350-361

[17] Carson, T.B., Marasco, D.E., Culligan, P.J., et al., 2013. Hydrological performance of extensive green roofs in New York City: Observations and multi-year modeling of three full-scale systems. Environmental Research Letters. 8(2), 024036. DOI: https://doi.org/10.1088/1748-9326/8/2/024036

[18] Viessman, W., Lewis, G.L., 2002. Introduction to hydrology. Pearson: London.

[19] Tuner, W.C., Malloy, J.F., 1981. Thermal insulation handbook. Krieger Publishing Co: Malabar, FL.

[20] Del Barrio, E.P., 1998. Analysis of the green roofs cooling potential in buildings. Energy and Buildings. 27(2), 179–193. DOI: https://doi.org/10.1016/S0378-7788(97)00029-7

[21] Green Roofs in the New York Metropolitan Region [Internet]. Columbia University Center for Climate Systems Research; 2004. Available from: https://www.researchgate.net/profile/Franco-Montalto/publication/251644778_Hydrologic_Functions_of_Green_Roofs_in_New_York_City/links/00463538c5f8d32bd2000000/Hydrologic-Functions-of-Green-Roofs-in-New-York-City.pdf

[22] Liptan, T. (editor), 2003. Planning, zoning and financial incentives for ecoroofs in Portland, Oregon. The First North American Green Roof Infrastructure Conference, Awards and Trade Show: Greening Rooftops for Sustainable Communities; 2003 May 29–30; Chicago, IL, United States.

[23] Wong, N.H., Chen, Y., Ong, C.L., et al., 2003. Investigation of thermal benefits of rooftop garden in the tropical environment. Building and Environment. 38(2), 261–270. DOI: https://doi.org/10.1016/S0360-1323(02)00066-5

[24] Takakura, T., Kitade, S., Goto, E., 2000. Cooling effect of greenery cover over a building. Energy and Buildings. 31(1), 1–6. DOI: https://doi.org/10.1016/S0378-7788(98)00063-2

[25] Theodosiou, T.G., 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings. 35(9), 909–917. DOI: https://doi.org/10.1016/S0378-7788(03)00023-9

[26] Wilmers, F., 1990. Effects of vegetation on urban climate and buildings. Energy and Buildings. 15(3–4), 507–514. DOI: https://doi.org/10.1016/0378-7788(90)90028-H

[27] Niachou, A., Papakonstantinou, K., Santamouris, M., et al., 2001. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings. 33(7), 719–729. DOI: https://doi.org/10.1016/S0378-7788(01)00062-7

[28] Meier, A.K., 1990. Strategic landscaping and air-conditioning savings: A literature review. Energy and Buildings. 15(3–4), 479–486. DOI: https://doi.org/10.1016/0378-7788(90)90024-D