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ARTICLE

Irrigation and Thermal Buffering Using Mathematical Modeling

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ABSTRACT

Two methods of irrigation, drip, and sprinkler were studied to determine the response of the Javits green roof to irrigation. The control study was dry unirrigated plots. Drip irrigation consisted of irrigation tubes running through the green roof that would water the soil throughout and sprinkler irrigation used a sprinkler system to irrigate the green roof from above. In all cases, the irrigated roofs had increased the soil moisture, reduced temperatures of both the upper and lower surfaces, reduced growing medium temperatures and reduced air temperatures above the green roof relative to the unirrigated roof. The buffered temperature fluctuations were also studied via air conditioner energy consumption. There was a 28% reduction in air conditioner energy consumption and a 35% reduction in overall energy consumption between dry and irrigated plots. Values of thermal resistance or S were determined for accuracy and for this study, there was little change which is ideal. A series of infrared and thermal probe measurements were used to determine temperatures in the air and sedum. It was determined that sprinkler irrigation did a better job than the drip irrigation in keeping cooler temperatures within the green roof. A Mann-Whitney U test was performed to verify the variation in moisture temperatures buffering energy consumption. By getting a p-value < 0.05, it indicates that the model is accurate for prediction and medium temperatures were statistically different.

Keywords: Green roofs; Irrigation; Drip; Sprinkler; Thermal buffering

1. Introduction

Green roofs have emerged as a promising solution to address a myriad of urban environmental challenges, offering a multifaceted approach that combines sustainability and innovation [1]. Recent research has delved into novel methods and strate-

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gies to enhance the performance and sustainability of green roofs, shedding light on their potential to transform urban landscapes into more eco-friendly and resilient environments. The materials and hydrological performance of green roofs have become focal points of investigation. Zhang and Chen [2] conducted a comprehensive review, emphasizing the significance of the materials used and their hydrological attributes. Such insights are essential for understanding the environmental benefits associated with green roofs. Furthermore, Wang, Guo, and Cao [3] provided an expansive review that underscores the role of green roofs in improving the urban environment. Their research encompasses various environmental aspects, making it highly pertinent to discussions on the potential advantages and drawbacks of this technology. These insights are essential for understanding the benefits of having green roofs. It was determined that green roofs significantly reduce indoor temperatures during hot summer months [4]. They act as an insulating layer, reducing the transfer of heat from the external environment to the interior of the building. This effect contributes to a more comfortable living environment and can result in decreased energy consumption for air conditioning [3,5].

Sustainable development is a key consideration, and Liu, Liu, and Cao [6] delve into the viability of green roofs. Their research outlines the crucial factors contributing to the sustainable growth of this technology, elucidating its prospects for the future. Urban stormwater management is another pressing concern that green roofs can address. Bass and Lee [7] offer valuable insights into their potential in this context, highlighting the role of green roofs in managing and mitigating urban stormwater runoff. The thermal performance of green roofs is also a subject of interest, particularly in diverse climatic conditions. Wu, Huang, and Zhang [8] have explored how green roofs influence heat transfer and thermal comfort in varying climates. Their findings offer practical data that can guide the effective implementation of green roofs in different environmental contexts.

The use of green roofs has the disadvantage of constant irrigation. In contrast, this technology contributes to the cleaning of rainwater, reducing pollution, lowering carbon emissions, improving the thermal and acoustic comfort, and lowering the temperature of external environment [9]. A field size of about 0.25 m, with robust balances of sensitivity of about 1–2 g, and a maximum weight load of 60 kg was measured by lysimeters [10]. These lysimeters were suitable for measuring various types of green roofs and could be used to measure light rain events as well as the dew on the vegetation in the morning hours. It was found that the irrigation system should be stopped 3 days before a rain event so the potential water capacity of the soil GR is high. Dry summer irrigation reduces temperature by up to 5 °C and on the vegetation layer up to 10 °C [10].

Thermal regulation flux affects vegetation and irrigation by less than 25% of the potential ET is applied as limited irrigation lowers heat flux [11]. Plant diffusion increased the thermal insulation capacity. [illegible] limited irrigation treatment was shown to increase thermal insulation capacity when compared to complete well-watered irrigation, suggesting that the air/water substrate has a greater effect on insulation than ET. Height, LAT and transpiration notes should be considered [12]. GR thermal insulation modeling (experiment) selection of plant species may be important. Heat reduction by evaporative cooling from GR (extensive) was explored by J. Heusinger et al. [13] by applying irrigation in different climate zones. There were three irrigation models: 1) no irrigation, 2) sustainable irrigation by harvested runoff, and 3) unrestricted irrigation. These models were used to study heat reduction potential in terms of surface energy partitioning and sensible heat flux and compare white roofs. Green roofs compared to black roofs reduced excess heat by 15–51% with sustainable irrigation by 48–75% unrestricted irrigation but dropped 3% unirrigated [13]. T. Sun et al. [14] confirm that the medium layer depth affects heat and moisture transport significantly. They found a deeper layer to redistribute more water into the bottom section, thus limiting surface evaporation, while a thin layer does not store enough water, dries up fast, and decreases performance. Therefore, an optimal layer thickness exists somewhere in the middle. The different irrigation scenarios are then investigated, given a fixed medium layer depth. Higher irrigation control limits (i.e., soil moisture at which irrigation is initiated) enhance the thermal performance of green roofs, but this enhancement plateaus at high limits [14,15]. Using a low-speed wind tunnel and the plant's transpiration, the thermal performance of the green roof was evaluated in the controlled weather conditions [16]. Green roof samples with two types of plants were tested. The results showed that plants' evapotranspiration represents about 13% of the thermal resistance for ryegrass and about 27.7% of the thermal resistance for periwinkle. Greywater was about 30% lower in temperature than those irrigated with clean water shown by their thermal performance for green roof irrigation [16]. From the top surface of the soil to the ceiling inside the chamber, temperature profiles were measured across the section of each roof. A comparison of the two shading strategies demonstrated that while the mesh provided more cooling over a daily cycle, the daytime cooli[illegible] potential, which is crucial in a desert climate, wa[illegible] higher with lightweight gravel [16].

In a study in a green roof module [illegible] com-mercial substrate types or systems were subjected to three irrigation methods (ove[illegible] d[illegible] sub-irrigation) to determine [illegible]strate [illegible] distribution and retention. Sub[illegible]ates subjected [illegible]ver-head irrigation or thos[illegible] w[illegible] moisture retention fabric (MRF) retained [illegible]e grea[illegible]ount of water. Sub-irrigation res[illegible] in the least [illegible]unt of water retention and t[illegible]e mo[illegible]t wastewater, except when an MRF was [illegible]. S[illegible]trate volumetric moisture content exhibite[illegible]ilar res[illegible]ts. The MRF was effectiv[illegible]taining [illegible] but for sub-irrigation a vis[illegible]le wa[illegible]front was [illegible]ot visible as water did not [illegible] e s[illegible] capillary action [17]. Differences can b[illegible]buted to the fact that overhead irrigation distribute[illegible]r over 100% of the area, whereas in many cases [illegible]e waterfront radiating from the drip or sub emitters never merged leaving dry areas In be-tween emitters [18]. Results show that overhead was the most favorable for plant growth and health [19]. 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 [17].

C. Van Mechelen et al. [20] concluded [illegible] ir-rigation may be a better choice, as it [illegible]stributes [illegible] more uniformly and leads to high[illegible]trate wa[illegible] holding capacity (WHC), less [illegible]off, an[illegible]er pla[illegible]t growth and health compar[illegible]d to drip irriga[illegible]An-other strategy to adapt to [illegible] irriga[illegible]on req[illegible]ire[illegible]ent is by optimal design of green [illegible]aterials, [illegible]ch as de-veloping green ro[illegible] substrates [illegible] hig[illegible]er WHC [21]. The addition [illegible]dy loam so[illegible]nd the use of amended soi[illegible] (i.e., [illegible]x of red gravel, vermiculite and bark [illegible]ompost), pe[illegible]based substrates, foam sheets and fiberglass can al[illegible]mprove the WHC of the gree[illegible] roof system. Some water-holding additives, like [illegible]drophilic ge[illegible]s, are also currently being ex-plore[illegible] A second way to conserve water is by find-ing alter[illegible]rrigation sources. For example, gray water, which is the wastewater from in and around [illegible] (including bathroom sinks, showers and washing machines, but excluding water originating from toilet flushing, dishwashers, and kitchen sinks), could be reused for irrigation purposes [20]. 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 [22]. 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, such as the stress point, which is the point when the transition between readily available water in the substrates larger pores and less available water in the small pores occurs). Irrigation can be controlled using a smart controller, which turns on when necessary (at night or when soil moisture drops below the stress point) but deactivated when rainfall is registered [23].

During the establishment phase and the first growing season throughout 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 temperate climates with dry periods [24]. In this study on Javits Convention green roof, 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 conference center was determined for the irrigation activities and the savings in cost.

A mathematical model is presented to compare the results of thermal buffering to a 2018 model using the error function [25]. There was a good correlation found between these two models. Eumorfopoulou and Aravanteuos [26] calculation has been completed, using the stationary method 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. This was also [illegible] recently verified by Wei and Ji [illegible].

This paper aims to contribute to the ongoing discourse on green roofs by exploring the impacts of different irrigation methods, with a specific focus on overhead sprinklers and dry irrigation, on the Javits Convention green roof. The study will assess the resulting effects on temperature, humidity, and energy consumption within the conference center, providing valuable insights into the benefits and challenges of these irrigation methods. As we advance our understanding of green roofs through recent research, we can harness their potential to create more sustainable and environmentally resilient urban landscapes. By integrating the latest findings into our study, we can make informed decisions that contribute to a greener, more sustainable future.

2. Methods

The JGR is an extensive green roof, and the key components are provided in Alvizuri [27]. A portable infrared camera was used to image the interior and exterior of the roof. The Javits Center's green roof layer consists of several layers: the top vegetation layer, vegetation mat, growing medium, water retention mat, and drainage layer. Below the green roof, the structure segment of the roof is positioned, such as bitumen, concrete, thermal insulation, and steel beam. The soil probes were calibrated in the same soil as the Javits roof under the sedum. The moisture was determined to have increased from 0.1 to 0.85 content by [illegible] using a gravimetric water content test. The thermal resistance for the green roof was determined using published values. The thermal resistance [illegible] equals 0.01[illegible] m^2k/w and the thermal transmissivity [illegible] .837 w/m^2k. The value of R and U for the Javits roof from the sedum mat the metal [illegible] 2.65 m^2k/w and 0.377 w/m^2k [27]. Although typical volumetric moisture content found in green roofs can vary for the range of R found on the Javits roof, the volumetric moisture content on the Javits roof has little change [28]. See Alvizuri [27] for the relationship between the diffusivity and U. Variation of temperature distribution through the green and structural Javits roof with a temperature of 29 °C was determined from the mathematical model [9].

The air temperatures were reported at six locations on a four-foot-high rectangular rack. See the experimental section for descriptions of the measuring equipment [29]. There was no temperature gradient difference observed between the two irrigation plots. The drip and sprinkler irrigation schedule is shown in **Figure 1** [29]. The dry temperatures were over 20 degrees higher than the wet plots. **Figure 1** [29] shows the location of the dry and wet plots and equipment locations used to measure moisture, humidity, air and soil temperatures, and AMPS in the RTU intake.

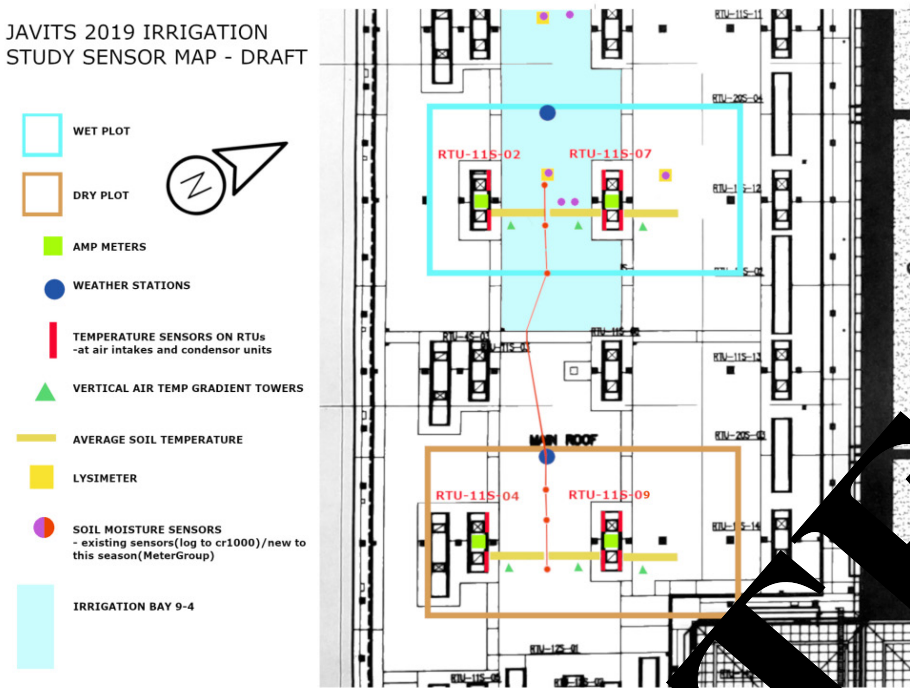


Figure 1. Layout of monitoring plan.

3. Results

A graph of the error function mathematical model is shown in Alvizuri [27] for three different roof temperatures. The moisture content of the irrigated plots was always higher than the dry plots (S4, S2). There was little change in the moisture for the air temperature during the survey. The values of the air temperature and relative humidity measured on the weather station are given in the experimental section.

From **Figure 2** it can be determined that there are higher values of the available kW per unit for 8/14 through 8/1[illegible] occupancy status of S2 and S4 differed significantly over the study period. S4 also showed operational challenges during the monitoring period. Operation of S7 and S9 were comparable during the monitoring with the occupancy differing only on one day during the study period.

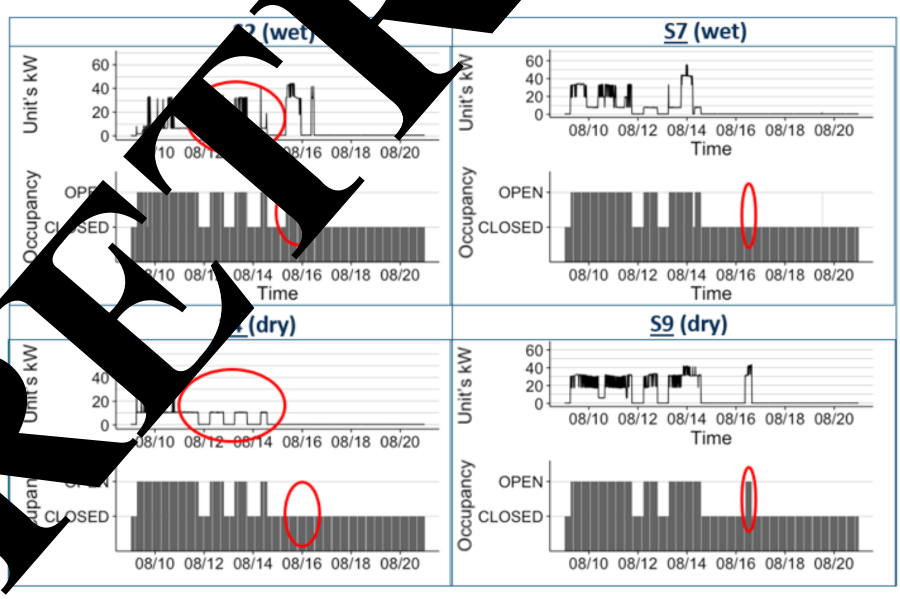


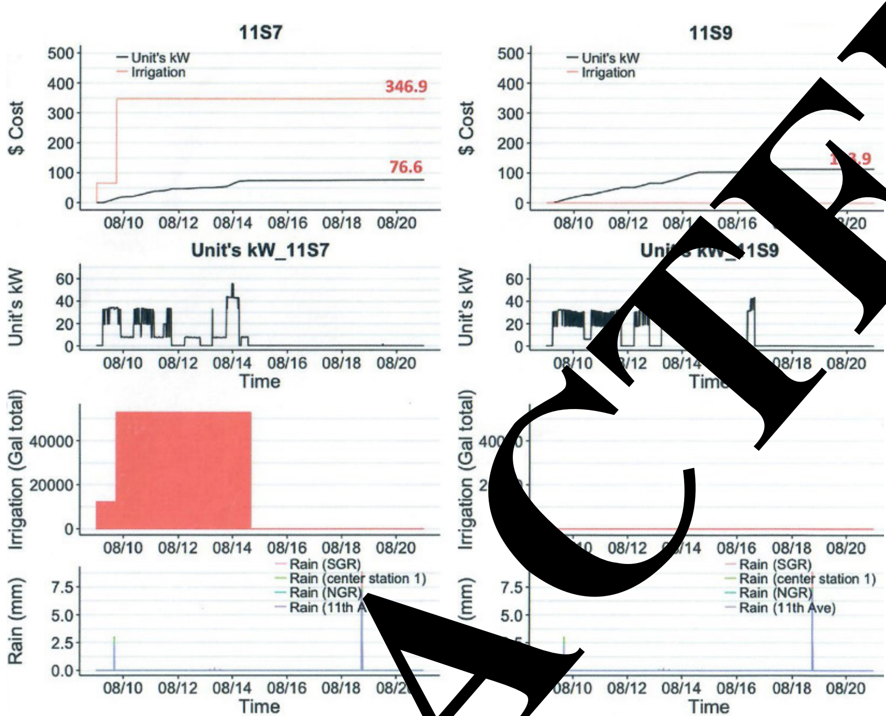
Figure 2. kW consumed and occupancy status.

There is also a 33% reduction in energy consumed between the two units (but the same irrigation activity benefits multiple units) shown in **Figure 3** (S7 is wet, S9 is dry).

There was no gradient observed between two different unirrigated plots. The thermal resistance R in $\frac{m^2k}{w}$ and thermal transmittance U in $\frac{w}{m^2k}$ was calculated for the five layers of green and six layers of structural roof for the JGR. The table of values for R is given in **Table 1**.

For the five layers of the green roof system, R is 0.108 and U is 9.837. These values were used to determine the value of the thermal conductivity α in Equation (1) [27].

$$\alpha = \frac{k}{\rho C_p} \tag{1}$$



[illegible] Comparison between S7 and S9.

T[illegible]es for Javits roof.

Item	d (m)	K (w/mk)	R
Sedum mat	0.019	0.5	0.0038
Soil	0.0119	1.16	0.01026
Fleece	[illegible]14	0.5	0.028
Drain mat	[illegible]	0.5	0.0254
Base felt	0.0093	0.07	0.133
Vermiculite a[illegible]te	0.036	0.094	0.383
Polystyrene foam	0.0762	0.045	1.693
Insulat[illegible]ncrete	0.0085	0.2	0.0425
A[illegible]phalt m[illegible]rane	0.0127	0.75	0.0169
[illegible]very b[illegible]	0.0127	0.045	0.282
Me[illegible]	0.0068	54	0.000126
		Sum R	2.653
		U	0.377

where:

k = thermal conductivity

ρ = density

C_p = specific heat capacity

The α values were used to determine the temperature variation in the green roof for each layer in the error function equation and are given in **Figure 4** with the upper layer of the green roof showing a sharp drop in temperature from the surface of the roof to the ceiling of the convention center.

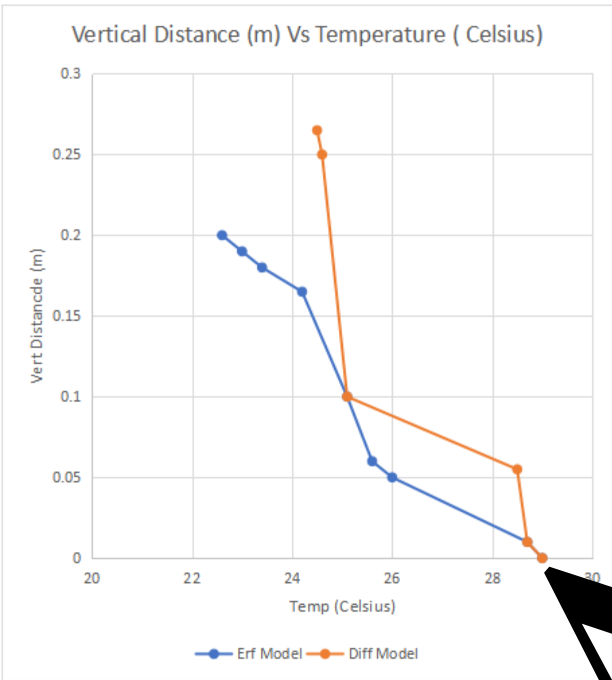


Figure 4. Vertical distance vs tem[illegible]

Variation of temperature dist[illegible]tion t[illegible]ough the green and structural Javits roof [illegible] be [illegible]perature of 29 °C was de[illegible]mined [illegible]e mathematical model [9]. The[illegible]re only a few [illegible]mputer simulations in the li[illegible]ratu[illegible] which the results of a simulation give[illegible] in [illegible] Alvizu[illegible]al. [27,29] to determine values o[illegible] the temperature v[illegible]ation through a green roof [illegible]d ca[illegible]lation[illegible] of R and α as shown in **Table 1**. T[illegible]alues have [illegible]een used in the determination of ET [illegible]e roof and the calculation of the Pe[illegible]onteith [illegible]tion for the water balance. [illegible]e ET [illegible]r the water balance is less than three perc[illegible]f [illegible] and precipitation.

In[illegible]d photos of the north and south roofs and ceilings a[illegible] shown in J. Alvizuri et al. [27] before the sedum was installed on the south roof. The average temperature of the south roof was 16.5 °C higher with the ceiling temperature 12.1 °C higher than the North roof. When the sedum was installed on the south roof, the difference in the roof and ceiling temperature was within experimental error. The temperature of the ceiling under wet plots is consistently lower than under dry plots.

One experimental study took place at the Cooper Union and involved the construction [illegible] a two[illegible]od-el roof: half of this area was a n[illegible]egetated c[illegible]rol section, and the other half was coa[illegible]ith geom[illegible]m-brane, soil, and sod, to simul[illegible] green r[illegible] ac[illegible] as a source of simulated rainf[illegible]l, a 4[illegible] × 4' grid of [illegible]C pipes was built and placed [illegible] the [illegible]f m[illegible]el. The roof model is on a 2% [illegible]pe, w[illegible]oles at [illegible]e bottom for runoff collectio[illegible] A uniform le[illegible] precipitation was applied to b[illegible]s over five tr[illegible]ls. Reference John Alvizuri e[illegible]l. [27] h[illegible]iew of the lab model, showing the ove[illegible]d rain make[illegible]

5[illegible]Discussio[illegible]

[illegible]error fu[illegible]ction mathematical model [9] was used t[illegible]te 53 pairs of internal surface temperatures. On average, the model predictions were within [illegible]e measured values. This validation indicates that [illegible]he error function mathematical model is very accurate at predicting the ceiling temperatures of this green roof and the temperature heat diffusion profile through the layers of the structure. From the results from Alvizuri [27], the differential model can be used with similar results of accuracy.

Equation (2) was used to compare the results to the results [29]:

$$\frac{d^2T}{dx^2} = 0 \tag{2}$$

where T is temperature and x is vertical distance (Holman, 1981). Solving the differential equation gives the relationship between temperature and distance is linear as following Equation (3):

$$T = Cx + vw\,D \tag{3}$$

where C and D are both constants. Since only how much temperature is changed by each layer is of interest, only the constant C will be discussed further.

Among several data sets, one of the planted roofs with medium-high vegetation with thermal insulation is selected, because its setting is similar to the Javits Center. The thermal behaviors of green roofs of many buildings in Greece [26] are analyzed by measuring temperatures at different layers throughout the green roof. It gives data on how temperature gets affected by each layer. Also, only summer data is selected, because the project is concentrated on the green roof's cooling impact on the building. From the data given, the slope of temperature through each layer is calculated, with the unit of °C/m. All the slopes come out to be negative, meaning the temperature cools throughout the depth of the green roof. **Table 2** summarizes the results.

Table 2. Temperature gradient slopes through each layer of the Greek building.

Layer	Temperature Slope (°C/m)
Soil	–1.67
Drainage	–4
Membrane protection against the roots	0
Bitumen membrane	–33.3
Perlite-concrete	–10
Foam expanded polystyrene	–75
Reinforced concrete slab	[illegible]0.67
Roof plaster	[illegible]

The two mathematical models are shown in a graph (**Figure 4**). There is a close comparison between these models. Van Woert et al. [19] ran tests on three roof models at a slope of 2% and found that vegetative roofs retained 66.6% rainfall; media roofs retained 50% rainfall and the gravel ballast roof retained 27.2% rainfall.

Figure 5 shows plots taken wi[illegible]emperature ranging from 26 °C to 48 [illegible]C on Augu[illegible]9 by the IR camera.

The sedum data indica[illegible]that o[illegible]day, [illegible]he S7 plot is over 14 °C hig[illegible]er th[illegible]n the wet p[illegible] at 13:00 and between 15:00 [illegible] 16:[illegible] hours. This leads to an indoor ceilin[illegible] differ[illegible] of abou[illegible] 4 °C at 13:00. The wet sed[illegible]m plots consi[illegible] have roof sedum temperatu[illegible] higher dry [illegible]eadings greater than 10–15 [illegible] and in[illegible] ceiling temperature of 3–4 °C comp[illegible]ed to the dr[illegible]s. Similar variations were [illegible]etermined for S6 and S9 plots. These temperature [illegible]eductions wer[illegible] recorded using the sprinkler irri[illegible]ion. There [illegible]as a similar temperature reduction u[illegible]ip irrigation with sedum roof having a temperature on the dry sedum of 5–10 °C higher than [illegible]he wet and 2–3 °C plots higher on the dry ceiling [illegible]erature. These values were repeated for different days (August 9 and 12) showing similar temperature reductions due to irrigation. The sprinkler always reduces the temperature more than the drip irrigation (**Figure 6**).

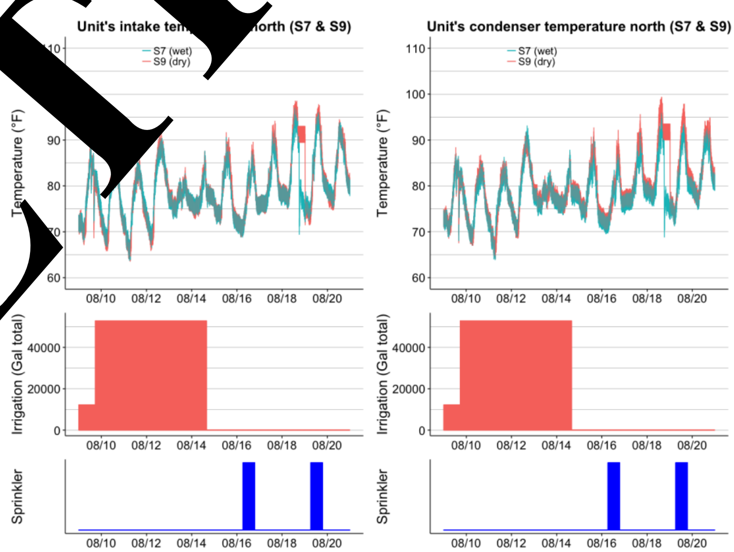


Figure 5. Air temperature above the green roof.

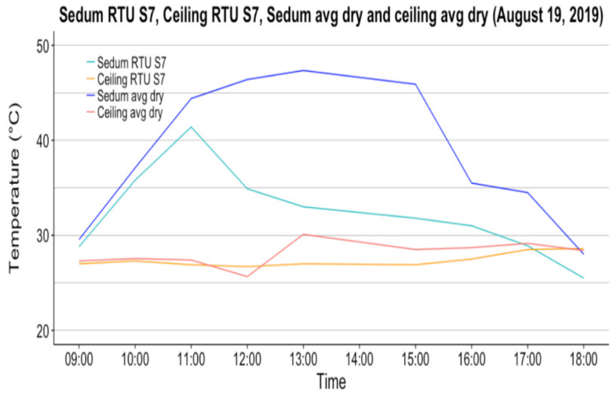


Figure 6. Comparison of drip to sprinkler irrigation.

In **Figure 7**, the temperature variation over a ten-day period (August 10 to 20) on the top and bottom of the sedum is shown for plots S2 (irrigated) and S4 (unirrigated). From August 10 to August 14, drip irrigation on 8/16 and 8/20 sprinkler irrigation was conducted. The difference in the wet versus dry for drip irrigation for the top sedum was less than 6 °C and for the sprinkler was over 17 °C. The bottom of the sedum in **Figure 7** had values for a drip irrigation 3 °F lower and a maximum 7 °F lower for sprinkler irrigation. The max temperature variati[illegible] for the bottom of the sedum for both drip and spri[illegible] irrigation varied from 5 to 17 °C lower than the [illegible]p of the sedum.

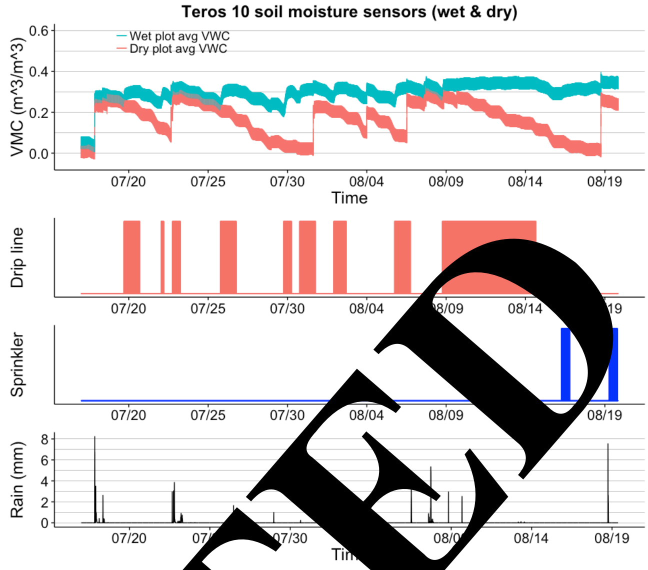


Figure 7[illegible]arison of the cei[illegible]g temperatures.

Table 3 [illegible]summa[illegible] the Mann-Whitney U tests' result[illegible]etermine if [illegible]e were statistically signific[illegible]nt differences in the median of the sedum temp[illegible]atures at the t[illegible]p and bottom in each region and b[illegible]en irrigated and non-irrigated regions. Instances, [illegible] the [illegible]-value is less than 0.05, indicate that median temperatures were statistically different [30]. [illegible]e U test proves that p-values less than 0.05 in[illegible] that the model is accurate in its predictions. In each region, the median temperatures at the top

Table 3. [illegible]sults of [illegible]itney Man[illegible] test at top and bottom of sedum.

Hypothesis	Drip [illegible] (Daytim[illegible]	[illegible]p Line Period (Nighttime)	Sprinkler Period (Daytime)	Sprinkler Period (Nighttime)
Temperature at the top and b[illegible]m of sedum in	P-value			
Irrigated	[illegible]milar (< 0.001)	Not similar (< 0.001)	Similar (0.087)	Not similar (< 0.001)
Non-irrigated	Not [illegible]ar (< 0.001)	Not similar (< 0.001)	Not similar (< 0.001)	Not similar (< 0.001)
Non-irrigated[illegible]	-	-	Not similar (< 0.001)	Not similar (< 0.001)
Temperat[illegible]op of sedum between	P-value			
Irri[illegible] non-irrig[illegible]	Not similar (0.001)	Similar (0.756)	Not similar (< 0.001)	Not similar (< 0.001)
[illegible]rigated a[illegible] non-irrigated	-	-	Not similar (< 0.033)	Not similar (0.015)
[illegible]ttom of sed[illegible]een	P-value			
Irrigated [illegible]on-irrigated	Not similar (< 0.001)	Not similar (< 0.001)	Not similar (< 0.001)	Not similar (< 0.001)
Irrigated a[illegible]d non-irrigated	-	-	Not similar (0.007)	Similar (0.173)

and bottom of the sedum were significantly different (**Table 3**) except for S1 during the sprinkler daytime period. A greater degree of variability was also observed at the top (**Figure 7**) and could be attributable that sedum itself effectively buffers temperature fluctuations.

The comparison of irrigated and non-irrigated plots suggested median temperatures were statistically significantly different, with only two exceptions: the comparisons of temperatures at the top of sedum between drip line nighttime, and at the bottom of sedum between sprinkler nighttime. This indicates that the sedum buffers temperature fluctuations.

Table 4 summarizes the results of Mann-Whitney U tests which determine the significance of the differences in the median of the ambient air temperatures between irrigated and non-irrigated regions. Instances where median temperatures were statistically different were drip line daytime for the entire tower (top, middle, and bottom) during sprinkler daytime for the entire tower and during sprinkler nighttime at the top and bottom of the tower.

The difference in maximum condenser temperature for irrigated and non-irrigated during drip line daytime ranged from –1.2 to 21 °C whereas the sprinkler period daytime ranged from 2.3 to 5.[illegible] °C. The Mann-Whitney U test suggested condenser temperatures were statistically significant during the sprinkler daytime and sprinkler nighttime [30,31]. The U test results for intake and condenser temperatures between irrigated and non-irrigated plots are given in **Table 3**.

A comparison of the ceiling temperature under irrigated and non-irrigated was completed. The fluctuation in the ceiling temperatures for both irrigated and non-irrigated plots displays similar patterns. The temperature of the ceiling was significantly different and consistently lower. The maximum temperature during the drip line daytime was 29 °C and 30 °C for the irrigated and non-irrigated plots, respectively. The difference in maximum ceiling temperature during drip line daytime ranged from 0.6 to 1 °C and for the sprinkler period daytime ranged from 1 to 1.7 °C.

6. Conclusions

The differential function equation is compared to the [illegible] function curve showing a close correlation to the two different methods. Since water can either travel through some layers without any hindrance, such as the drainage layer, or cannot penetrate at all into a layer, such as the structure portion of roof, hy-

Table 4. Results of Whitney Mann U test at the top of the tower.

Hypothesis	**Drip Line (Daytime)**	**Drip Line (Nighttime)**	**Sprinkler (Daytime)**	**Sprinkler (Nighttime)**
Temperature at the top of tower in	P-value			
Irrigated S1 and non-irrigated S4 are	Similar (0.147)	Similar (0.270)	Not similar (< 0.001)	Not similar (< 0.003)
Irrigated S2 and non-irrigated S5 are	Not similar (0.003)	Similar (0.123)	Not similar (< 0.001)	Not similar (< 0.001)
Irrigated S3 and non-irrigated S6 are	-	-	Similar (0.958)	Similar (< 0.059)
Temperature at middle of tower in	P-value			
Irrigated S1 and non-irrigated S4 are	Similar (0.712)	Similar (0.234)	Not similar (< 0.001)	Similar (0.860)
Irrigated S2 and non-irrigated S5 are	Not similar (0.024)	Similar (0.140)	-	-
Irrigated S3 and non-irrigated S6 are	-	-	-	-
Temperature at the bottom of tower in	P-value			
Irrigated S1 and non-irrigated S4 are	Similar (0.103)	Similar (0.234)	Not similar (< 0.001)	Similar (0.860)
Irrigated S2 and non-irrigated S5 are	Not similar (0.025)	Similar (0.898)	-	-
Irrigated S3 and non-irrigated S6 are	-	-	Similar (0.658)	Similar (0.463)

draulic parameters of such layers are not acquirable. In this case, heat transfer theory has been used to predict the temperature gradient [32]. There is no heat generation source within each layer, the temperature gradient in only one direction, vertical direction, is of interest, and steady state is chosen to be analyzed; therefore, the heat transfer equation of steady-state one-dimensional heat flow with no heat generation is used.

Figure 1 shows the layout of the drop and sprinkler irrigation and the layout of the Javits 2019 roof. **Figure 2** shows that there are higher values of the available kW per unit for 8/14 through 8/16. There is also a 33% reduction in energy consumed between the two units (but the same irrigation activity benefits multiple units) shown in **Figure 3** (S7 is wet, S9 is dry). The *α* values were used to determine the temperature variation in the green roof for each layer in the error function equation and are given in **Figure 4** with the upper layer of the green roof showing a sharp drop in temperature from the surface of the roof to the ceiling of the convention center. **Figure 5** shows plots taken with the air [illegible]perature ranging from 26 °C to 48 °C on August 19 by the IR camera. **Figure 6** shows the sprinkler always reduces the temperature more [illegible] the drop irrigation. A comparison of the ceiling temperature is shown in **Figure 7** for plots S2 and [illegible] from [illegible] 10 to August 20, 2019. The maximum temperature for the dry plot was 86°F and the wet plot [illegible] 84°F. The fluctuations in the ceiling temperatures under both plots display the same patterns. The wet plots' ceiling temperature is consistently lower than under the dry plots. Sedum effectively buffers temperature fluctuations. [illegible]se temperatures were measured with the probes.

The results in [illegible] compare favorably with Abualfaraj [29]. A different mathematical model was [illegible] to c[illegible] the results to the error function model [illegible] Abualfaraj [29] with interesting results. By using a [illegible]nt temperature model approach compared to Abualfaraj [29] and the effects of irrigation the following benefits of a green roof were determined:

- Increased the moisture content.
- Reduced the growing media temperature.
- Reduced the temperature of its upper and lower surfaces.
- Reduce the air temperature just above it.
- Reduce the ceiling temperature under the irrigated roof plots.

Over a 10-day test, these differences am[illegible]ed to a 28% reduction in air cond[illegible] energy c[illegible]sumption and there was a 33% redu[illegible] in energy consumption between dry and wet plot [illegible]. The Mann-Whitney U test was used to verify the conclusions of the variation [illegible] moisture, temperature buffering and energy consumption with values of $p < 0.05$. An error function mathematical model was used to determine [illegible] behavior of the thermal buffering of the [illegible]GR. The model was used to predict 53 pairs of internal temperatures [27]. This model has a close comparison to the differential equation model. The differential function is compared to the error function curve showing a close correlation to the two different methods. By using irrigated green roofs, the effects of climate change can be adapted to and even [illegible]igated. Irrigation activities were effective at keeping [illegible] growing medium moist during the dry periods with a better than 3% accuracy. The soil moisture increasing in response to precipitation was elevated in the green roof due to irrigation and increased the roof's ability to become a thermal buffer. In addition, green roofs help mitigate storms, reduce energy use by buildings, mitigate the heat island effect, establish habitats for birds and bees, and increase water and air quality. By continuing to implement green roofs with sprinkler irrigation, we will be able to reap the full benefits of green roofs as we continue to adapt to the changing climate.

7. Limitations

The use of green roofs has the disadvantage of constant irrigation. The lysimeters were only suitable for measuring various types of green roofs and were used to measure light rain events as well as the dew on the vegetation in the morning hours. The irrigation system should be stopped 3 days before a rain event so the potential water capacity in the soil green roof is high. The limited irrigation to lower heat flux is less than 25% of the potential ET. Height, LAT and transpiration should be considered. Plant species are important to the irrigation of green roofs. The climate should also be considered in the design of green roofs. Limiting surface evaporation does store enough water, dries fast, and decreases performance. The enhancement is high to limit irrigation. Daytime cooling was high and provided more cooling during the day with light-weight gravel.

Author Contributions

In this study, the author contributions were as follows:

Harsho Sanyal: Conceived and designed the research, collected, and organized research data, conducted data analysis, and wrote the manuscript.

Yara Elborolosy: Contributed to data analysis, contributed to manuscript writing, and reviewed the manuscript.

Joseph Cataldo: Contributed to the study design, data analysis, and provided critical revisions to the manuscript.

All authors reviewed and approved the final version of the manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this research. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors have no financial interests or relationships that could be perceived as influencing the research presented in this paper.

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