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# LABORATORY EXPERIMENTS AND MODELLING TO DETERMINE THE PROFILES OF THE JAVITS CENTER GREEN ROOF

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ABSTRACT
Climate change has led to triple digit temperatures globally, notably along the western coast of the United States. These changes have produced intense weather-related events such as fires and landslides. Green roofs are one strategy to mitigate these high temperatures. For this report, several studies were compiled, using data found from physical green roof models as well as on-site data from the Javits Center Green Roof. At the Javits Green Roof, an infrared camera was used to collect thermal images at various parts of the roof, to determine its effectiveness for thermal buffering. Off site, a rain simulator was used on model green roof and a control roof, to determine change in retention and peak runoff rate. The green roof was able to retain 2%–22% of rainfall and reduce peak runoff by 19%–28%. From the graph comparing roof temperatures, there were higher temperatures on the black top roof in comparison to the green roof, and the slopes of the lines indicated the mitigating effect of the green roof on heat waves. These models were also analysed with an infrared camera, which showed that green roofs can be, as much as 25°F cooler than their standard roof counterparts, providing valuable evidence for the usefulness of green roofs to combat heat waves. Runoff quality was experimentally measured using a green roof model, where nitrogen concentration is measured before and after to determine change in runoff quality. This concept is based on studies which claim that the addition of wood mulch to soil can reduce nitrogen content. This experiment revealed a 23% reduction in runoff nitrates for the wood-mulch treated soil, in comparison to a 6.5% reduction for the control roof. Furthermore, a mathematical model was used to determine the ceiling temperature of the Javits Center within 3%.
*Keywords: green infrastructure, green roof, infrared camera, thermal buffering, runoff.*

## 1 INTRODUCTION

The world is currently entering a period of rapid and significant change. The past 5 years alone have been the hottest 5 years recorded since major weather and climate agencies began to track global temperatures in the 1880s. July 2021 has been the hottest month ever recorded in history [1]. Scientists estimate that upon the conclusion of the 21st century, the average global temperatures will increase by at least 3°C [2]. To contextualize this rate of change, global temperatures have risen by a little over 1°C in the past 141 years [3]. An increase as projected would correspond with triple the number of weather-related events such as hurricanes, wildfires and heat waves. A multitude of regions are heavily affected by the shift in climate. Rising sea levels and worsening hurricane seasons are a threat to the Mississippi River Delta [4]. Many areas along the eastern coast of the United States are directly impacted by flooding from sea level rise. In Alaska, global warming and longer summers have caused the Arctic permafrost to melt [5]. The Amazon rainforest has existed for ten million years; it may not survive the next hundred.

The urban building environment is especially vulnerable to these climate extremes. Heat waves in particular have become more frequent, causing more frequent warm days and fewer cool days. The environmental baselines of cities have started to shift, to the point where cities are several degrees warmer than surrounding areas due to the urban heat island (UHI) effect [6]. There is also a reduction in evaporative cooling due to a lack of vegetation, as well as the production of waste heat.


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Green infrastructure (GI) has emerged as a viable option to combat the effects of climate change. It is designed to imitate natural hydrology, incorporating porous surfaces which can absorb up to 90% of the stormwater runoff that reaches them. In absorbing this runoff, GI reduces the stress on sewer systems and mitigates risk of flooding. The quality of the runoff is filtered through processes such as adsorption, filtration and plant uptake. GI can also generate positive effects such as air quality improvement (by absorbing pollutants from the air) and preservation of ecological habitats (by reducing erosion-causing runoff). In the context of rising temperatures specifically [7], GI provides increased resilience against climate change by combating UHI effect and reducing temperatures through evaporative cooling, while absorbing potential floodwater [8].

One form of GI is the green roof. Green roofs are multi-level roofing layers on buildings, coated with vegetation. Research concerning the thermal performance of green roofs in urban [9,10] and suburban settings is relatively new. The majority of this work underscores the thermal benefits of green roofs over traditional black tar asphalt and gravel roofs [11,12]. 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 [13]. 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 (its vegetation, growing media and the moisture stored within it) [14,15].

Water quality is another important parameter to measure the effectiveness of green roofs. Water quality can be quantified through many values, one of which being the level of nitrates in runoff. The effects of nitrates were studied from a variety of sources. As with other salts, nitrates in soil increase osmotic pressure outside of the plant roots, reducing the amount of water they can take in against the concentration gradient. Excess nitrogen can be leached out of the soil by runoff water, which can enter aquatic systems and cause rapid algal growth. This process, known as eutrophication, can lead to reduced dissolved oxygen levels and limited penetration of sunlight into the water. Processes for soil remediation vary [16]. For nitrate remediation, usage of wood mulch to tie up excess nitrogen was seen to be an effective strategy [8].

## 2 EXPERIMENTATION

The results of the field and laboratory studies at Cooper Union are provided in this paper. A series of laboratory experiments were conducted both on-site at the Javits Green Roof, as well as off-site.

Two studies took place at the Javits Center Green Roof (JGR) in 2017 and 2018, complemented by green roof models. During the 2017 study, weather stations were set up at the JGR, equipped with an anemometer, a rainfall sensor, a humidity sensor, a radiation sensor, a FLIR T440 thermal imaging camera, and an infrared thermometer. These stations recorded the following parameters: wind speed/direction, rainfall, radiation, air temperature, humidity, and temperature of the air, exterior roof surface and interior ceiling surface. The IR cameras collected exterior surface temperatures, which were correlated with air temperatures from the closest weather stations, and interior surface temperatures were correlated with air temperatures inside the Javits Center collected by thermometers. The difference in temperature between the exterior and interior surface was used to quantify thermal buffering of the roof. These on-site studies were complemented by the construction of five physical models of the JGR in the Cooper Union laboratory, with lateral dimensions of 1.2 by 0.6 m. Results from this study found that the JGR had a substantial impact on reducing heat transfer through the Javits roof [14]

Runoff observations at the JGR were compared with the results from a computer model, which predicted peak runoff rates and total event runoff within +25% to 15% and +10% to 20%, respectively. This study found that, on average, 96% of rainfall was retained for events less than 6.35 mm, while 27% was retained for events greater than 12.7 mm [17]. This study provided strong evidence for green roofs' capacity for stormwater retention.

One experimental study took place at the Cooper Union, and involved the construction of a two-part model roof; half of this area was an unvegetated control section, and the other half was coated with geomembrane, soil and sod to simulate a green roof. To act as a source of simulated rainfall, a 4' × 4' grid of PVC pipes was built, and placed above the roof model. The roof model is on a 2% slope, with holes at the bottom for runoff collection. A uniform level of precipitation was applied to both roofs over five trials. Figure 1 is a view of the lab model, showing the overhead rain maker.

The second experimental study for this paper also took place at Cooper Union, and examined a model green roof based on the JGR. The purpose of that study was to first investigate the effects of excess nitrogen on soil, and then to examine the effect of wood mulch on nitrate concentration in soil [8].

Two 2-foot by 4-foot boxes had holes drilled along one of the shorter ends. This end would be covered by a PVC pipe, to allow a path for runoff. These boxes were placed on a 3-degree incline and coated with felt to cover any cracks, after which they were both filled up to a height of 1 foot with soil. The upper layer of soil for Box A (the experimental box) was mixed with four quarts of wood mulch. Water mixed with soluble nitrates was poured over each box on the first trial date, and tap water was poured over each box on the second trial date. The parameters measured included nitrate concentration, pH and temperature for inflow/outflow, which were measured with nitrate test strips, pH test strips and a thermometer, respectively [8].

Figure 1: Roof model with asphalt shingles, root barrier and drainage map and thermistors [14].

## 3 RESULTS

To determine the behaviour of green roofs due to extreme heat conditions, the green roof and control roof were tested under a series of runoff and heat conditions (see section 2) For the runs tested the precipitation was varied as well as the rain and room temperatures. Table 1 shows the range of values for the runs considered and tested.

The following graph (Fig. 2) shows rain versus the green roof and control temperatures. Control has a larger slope (i.e., larger temperatures) compared to the green roof. The room temperature was held at 71°F.

Hydrographs were constructed for the green roof and control. One example of these hydrographs is shown in Fig. 3, with the graph data in Table 2. Each curve ends when the quantity of discharge accumulated during a given time interval is less than 100 ml. The accumulated percent retained and average lag time for each run was compared. These figures show hydrograph curves with best fit equations and $R^2$ values – all greater than 0.95 most over 0.99.

Table 1: Range of temperature values for all green roof and control runs.

| Trial | Surface temp. (°F) | Rain (in/day) | Room temp. (°F) | Rain temp. (°F) | Control roof temp. (°F) | Green roof temp. (°F) |
|---|---|---|---|---|---|---|
| 1 | 84 | 1.68 | 70.9 | 105 | 93.2 | 76.5 |
| 2 | 77 | 7.92 | 71.1 | 93 | 86.6 | 71.2 |
| 3 | 74 | 7.1 | 71.2 | 79.6 | 79.4 | 73 |
| 4 | 76 | 5.04 | 66.7 | 85.5 | 80.9 | 74 |
| 5 | 71 | 12.98 | 73.2 | 57.3 | 57.4 | 62.5 |
| | | 6.16 | 73.8 | 58.5 | 57.8 | 61.6 |

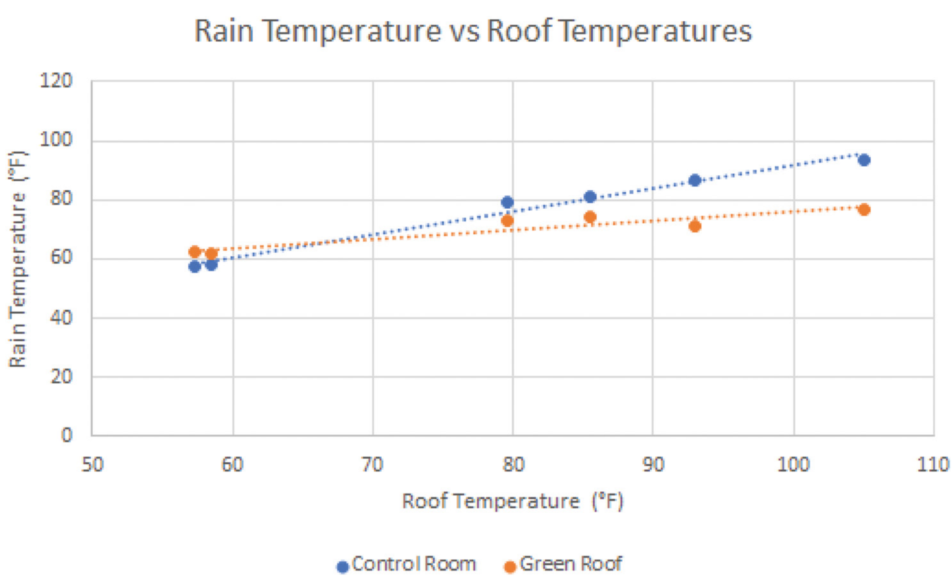


Figure 2: Rain temperature vs green roof and control roof temperatures.

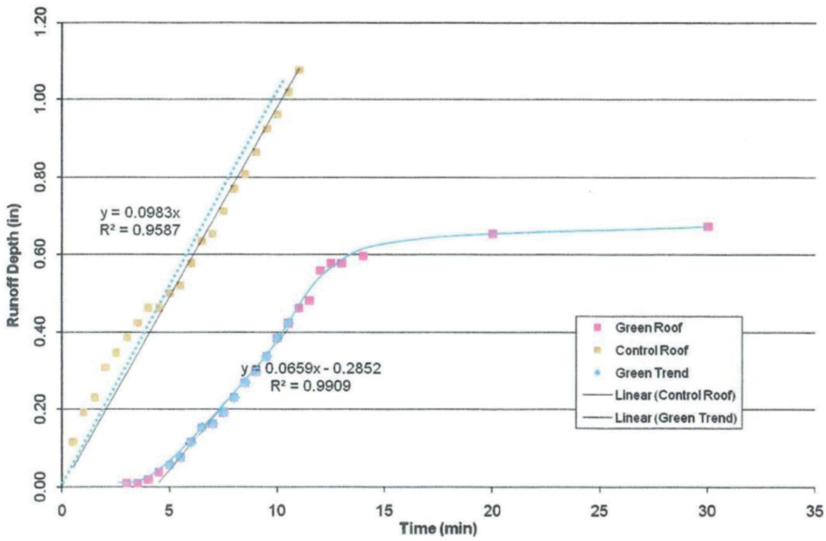


Figure 3: Hydrograph for an 11-minute storm.

Table 2: Hydrograph data for all trials.

| | Hydrograph line of best fit: roof temperature vs rain temperature | | $R^2$ | |
|---|---|---|---|---|
| Trial number | Control roof | Green roof | Control roof | Green roof |
| 1 | $y = 0.133x$ | $y = 0.1422x - 0.1703$ | 0.9966 | 0.9845 |
| 2 | $y = 0.1226x$ | $y = 0.0993x - 0.1413$ | 0.9907 | 0.9872 |
| 3 | $y = 0.0983x$ | $y = 0.0659x - 0.2852$ | 0.9587 | 0.9909 |
| 4 | $y = 0.2162x$ | $y = 0.1408x - 0.2617$ | 0.9556 | 0.9904 |
| 5 | $y = 0.1054x - 0.9358$ | $y = 0.0937x - 0.7677$ | 0.9936 | 0.9909 |

The percent retained by the green roof ranges from 2% to 22%. The lag time ranges from 2 to 11 minutes. Studies have found that the intensity of rainfall also significantly affects the ability of green roofs to control stormwater. Green roofs are generally more effective at retaining Rainwater from small storms. For the first two runs there was 100% retention to 6 and 9 minutes. For the remaining runs, full retention was measured about 1 1/2 minutes from the start of rain. The Green roof delays the onset of runoff, shown by the lack of cumulative runoff curve compared to the inflow curve and also extends the hydrograph which indicates that green roofs retain the precipitation for a long time. Table 2 shows the retention and average lag time for each trial, while Table 3 highlights the peak runoff rates.

As seen from Fig. 3 and Table 4, the green roof reduces the peak runoff, with the reduction ranging from 19% to 28%. The slope of the cumulative runoff for the green roof is less steep than the inflow, which indicates that the green roof is able to reduce the rate of drainage volume.

Table 3: Green roof retention and lag time

| Run number | Total inflow (mL) | Cumulative runoff (mL) | % Retained | Average lag time (min) | Moisture Content |
|---|---|---|---|---|---|
| 1 | 26,330 ± 2,630 | 20,656 ± 2,085 | 22% | 11 | 49.0% ± 2.7% |
| 2 | 35,083 ± 3,520 | 27,353 ± 2,755 | 22% | 12 | 45.1% ± 4.7% |
| 3 | 17,023 ± 800 | 16,661 ± 725 | 2% | 2 | 56.2% ± 7.6% |
| 4 | 18,110 ± 800 | 17,241 ± 725 | 5% | 2 | 45.4% ± 19.6% |
| 5 | 17,023 ± 800 | 15,212 ± 725 | 11% | 3 | 48.6% ± 22.2% |

Table 4: Peak runoff rates.

| Run number | Peak inflow (mL/min) | Peak outflow, green roof (mL/min) | % Reduction |
|---|---|---|---|
| 1 | 1,188 | 880 | 26% |
| 2 | 2,250 | 1,730 | 23% |
| 3 | 3,780 | 2,716 | 28% |
| 4 | 3,343 | 2,717 | 19% |
| 5 | 5,433 | 5,433 | 0% (discarded) |

The nitrate experimental trials were carried out in the Cooper Union Fluids Laboratory. Table 4 shows data from the first trial date (with nitrogen-dissolved water), while Table 5 includes the measurements from the second trial date 2 weeks later, with tap water. From both tables, it is seen how runoff emerged in larger quantities from the box with wood mulch mixed in (due to the increased voids, and decreased retention capacity, caused by mixing the soil). The nitrate concentration in runoff decreased by 300 ppm in the wood mulch box, while it stayed similar to the initial value in the control box (shifting from 800 to 750 ppm). There were no significant changes in pH throughout the trials. During both weeks, the temperature of the runoff was 23°C, regardless of inflow temperature [8].

The infrared photo of the green roof and control model is shown in Fig. 4. The colour of the control roof on the right is red, with the temperatures in the mid-90s; this illustrates ponding of the heated water at the lower edge of the model. Ponding is when water pools, creating a "pond". The top of the control roof has lower temperatures (in the 80s), as there is no hot water ponding there. The green roof, in contrast shows green and blue colours, with temperatures in the mid-70s. There are a number of small red-yellow colours, indicating ponding of hotter water. The discharge overhead rain water pipe is at the top of the figure with temperatures in the mid-90s.

## 4 DISCUSSION

The three experiments conducted at the Cooper Union laboratory all provide information which can determine green roof parameters such as thermal buffering, runoff storage and nitrate remediation, on physical green roof models representative of the JGR. The models from the 2017 study examined the behaviour of a green roof in comparison to a control roof, and how conditions on the in-situ Javits roof were affected. The results were used as

Table 5: Flow data for Trial 1: nitrate water inflow into green roof [8].

| Trial 1 | | Quantity (mL) | Nitrate concentration (ppm) | pH | Temperature |
|---|---|---|---|---|---|
| Wood mulch-mixed soil | Inflow | 9,000 | N/A | 6.5 | 25 °C |
| | Runoff | 1,850 | 1,300 | 6.5 | 23 °C |
| Only soil | Inflow | 9,000 | 600 | 6.5 | 25 °C |
| | Runoff | 1,300 | 800 | 6.5 | 23 °C |

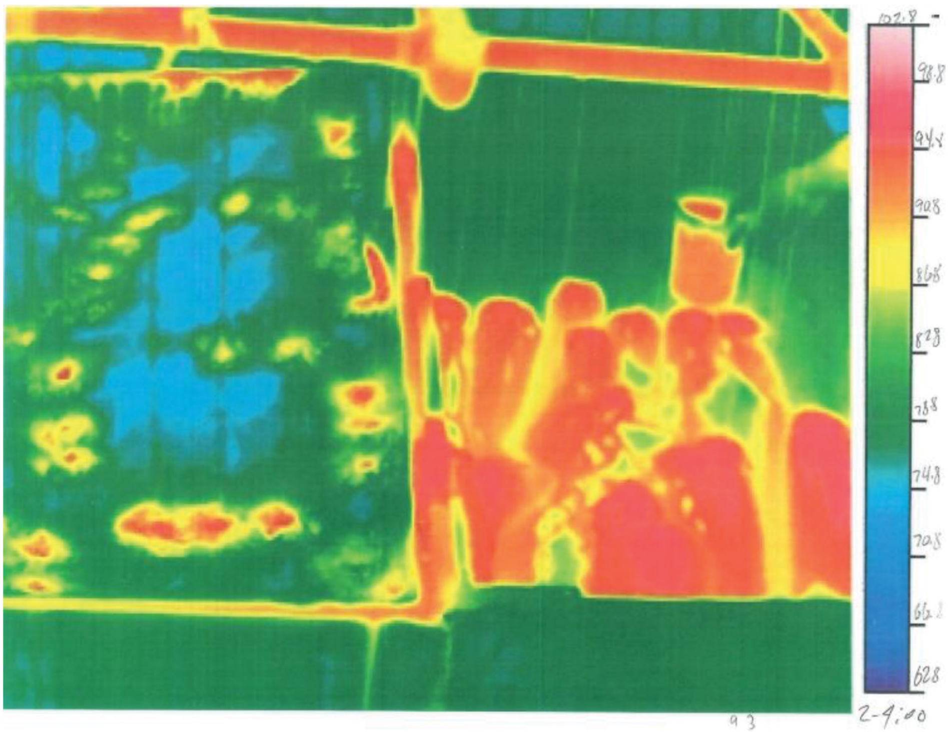


Figure 4: Infrared photo of green roof (left) and control roof (right) setup.

Table 6: Flow data for Trial 2: tap water inflow into green roof [8].

| Quantity (mL) | | Quantity (mL) | Nitrate concentration (ppm) | pH | Temperature |
|---|---|---|---|---|---|
| Wood mulch-mixed soil | Inflow | 9,000 | N/A | 6.5 | 24 °C |
| | Runoff | 2,360 | 1,000 | 6.5 | 23 °C |
| Only soil | Inflow | 9,000 | 600 | 7.0 | 24 °C |
| | Runoff | 1,460 | 750 | 6.5 | 23 °C |

parameters for an error function mathematical model [14,17]. The second study elaborated further on runoff retention and thermal buffering. Furthermore, the proximity of the Javits Center to the Lincoln Tunnel was taken into account. As such, there will be a high nitrate loading. The tests in the Cooper Union laboratory showed that the green roof can be managed to reduce this loading. Coupled with the thermal buffering and rainfall storage tests, these experiments can be used as a predictive tool of green roof behaviour, applicable on a larger scale.

During the on-site studies, 55% of the cumulative precipitation that fell on the green roof during the monitoring period was retained, with an average of 75.4%–79.3% of precipitation retained per event. Tests on three roof models run by Carson et al. [18] found that vegetated roofs held 60.6% of rainfall, while media roofs retained 50.4% and gravel ballast roofs retained 27.2%. Additional research can focus on variation of substrate depth and climate conditions, as deeper substrates would hypothetically lead to increased retention. It is possible, however that during the colder seasons (when there is less evapotranspiration), substrates will naturally be wetter from condensation, and runoff may actually occur from the green roof surface at saturation. As the current studies were carried out during the summer, this could not be determined, but should additional studies prove this hypothesis correct, it would reduce the importance given to substrate depth for rainfall retention [14]. Empirical relationships suggested that the green roof's ability to store moisture is directly related with the duration of the event's preceding dry period.

Each run is about 10 minutes long, to simulate a ten-minute storm. Rainfall rates are high, ranging from 1.6 to 13 minutes per hour. The discharge draining from the green roof has a constant temperature for each run and for 20 minutes after the storm. Since there is no albedo and little evapotranspiration, the mechanism to account for this is the transfer of heat from the soil to the green roof (including geotextile and drainage systems). The green roof discharge water is at least 2.5 times more than the control roof for runs with higher rain temperatures than room temperatures. The temperatures for all six runs go through the room temperature.

From the hydrograph data in Fig. 3 and Table 2, there is a lag time between the control and green roof model runs. The control response to the rain is rapid since there is almost no overland flow time. The green roof has a delay, i.e., the time difference in time between the control and green roof at the beginning of the hydrograph from 2 to 12 min. The ratio between the slopes of the control roof line and the green roof line varies from 0.94 to 2.3. The equations of best fit and R2 values are given in Fig. 3 and Table 2. There is a linear fit between the peak flows and ln of the slope. Therefore, we have a method to find peak inflow [peak outflow] in a green roof from this equation. From the IR photos and isotherms, the control roof is as much as 25°F warmer than the green roof.

The mitigation of the heat due to the green roof can be seen in the IR photo in Fig. 4. The deep red colour [temperatures in the mid-90s] on more than half of the control roof contrast to the green blue colour [temperatures in the mid-70s] on most of the green roof. This buffering of up to 25°F effect of the green roof is an advantage in controlling and reducing heat waves an is a serious consideration in the design of buildings and gardens in an urban environment.

Several strategies exist for nitrate remediation in soil. One method is by planting non-legume plants, which absorb nitrates in soil effectively [19]. Leafy greens can be especially useful for this purpose, as they tend to absorb large amounts of nitrogen; examples include carrots, kale and lettuce [20]. A third strategy is wood mulch, which can tie up nitrogen in soil, preventing it from leaching into runoff. For this research, wood mulch was used, due to its ease of application for experimental studies.

The runoff from the boxes had to be diluted with 20 mL of deionized water per 5 mL of runoff. For Box A (with wood mulch), the average nitrate concentration of the runoff changed from 1,300 ppm on Trial Date 1 to 1,000 ppm on Trial Date 2, showing a significant decrease of 23.1%. For the control group in Box B, with no wood mulch, the Trial 1 average nitrate level of 800 ppm changed on Trial Date 2 to 750 ppm, a reduction of only 6.25%. No conclusions can be drawn from the pH, as there was no significant change across both trial dates. According to previous research, use of nitrate-based fertilizers (as was added to the inflow in this experiment) have no potential for acidification, and may actually have the opposite effect when plants release $OH^-$ when absorbing hydrogen ions. However, this was not the case in the experiment, likely because there were no plants in the experimental setup, only soil [8]. The temperature of the runoff ending at 23°C for both boxes, despite the inflow temperature, shows that the soil temperature had an effect on the runoff temperature. There was a significant amount of inflow retention by both boxes, ranging from 74% to 85% [8].

The removal of excess nitrates from soil can be beneficial to improving soil health. By reducing the osmotic pressure, plants will be able to take in more nutrients, while also diverting less energy towards metabolizing nitrates. Eutrophication will also be mitigated, preventing excessive algal growth in the water and maintaining oxygen levels and sunlight penetration. Furthermore, nitrate leaching tends to also carry away other essential minerals such as sulphur – by preventing this outcome, the soil quality is maintained [8].

The error function mathematical model previously referenced is presented in the 2017 study, and used again as a predictive equation in the 2018 study [14,17]. It was first developed by Carslaw and Jaegar [23] and uses heat conduction principles. This model is a function of thermal conductivity, depth and heat exposure time. It is subjective to two boundary conditions. The temperature gradient in the sub-layers of the JGR was determined using this one-dimensional heat conduction model. This heat conduction model relies on the material properties of the roof. A sensitivity analysis was conducted by varying a number of green roof parameters such as depth, Javits Convention Center ambient temperatures, alpha values, and heat exposure times. There is little change in the ceiling temperature when these parameters were altered. The average change in the Javits Convention Center ceiling is less than 3%. When the ambient outside air temperature is less than inside of the convention centre, the roof acts as an insulator from cold air. A thicker foam layer makes for better insulation from heat source, but a larger change in depths of this results in a relatively smaller thermal change.

## 5 CONCLUSION

From the tests run on the Javits Green Roof, laboratory tests, and mathematical modelling the following conclusions are drawn:

- The surface of the green roof was 16°C cooler than the surface of the bitumen green roof, and also cooler than sidewalk surfaces by 5–10°C [14]
- From field observations, laboratory investigations and mathematical modelling, the cross section of the green roof is more effective for thermal buffering than the corresponding structural roof cross section (11.9°C vs. 9.0°C) [14]

These studies of the Javits Green Roof provide evidence for the claim that construction of green roofs can be seen as a win-win opportunity While the floor space inside the building is maximized for development, the rooftop can be used to simultaneously mitigate heavy rainfall and comply with the city's stormwater regulations. Some of these regulations are defined under NYC Local Laws 92 and 94 of 2019, which require that any roofing constructions or expansions must incorporate sustainable roofing systems; this means either solar panels, green roofs, or a combination of both [21]. Green roofs also allow the city to be better prepared to combat climate change (reducing UHI effect), along with other social and aesthetic improvements brought about from their construction [14].

The observations, modelling and analysis of the Javits Green Roof suggests that for some, building green roofs represent a win-win opportunity. By utilizing the building's rooftop space to mitigate incident rainfall, building owners can maximize developable floor space inside the building, while minimizing the cost to comply with current stormwater management requirements in New York City. Simultaneously, this same strategy can help prepare the city for climate change, while enhancing the city with the other co-benefits of this rediscovered approach to urban storm water management [14].

The error function model was used to simulate 53 pairs of internal surface temperatures. On average the model predictions were within 3% of the measured values as recorded during the experimental procedures [14,17]. This validation indicates that the error function mathematical model is very accurate in predicting the ceiling temperatures of the Javits Center and the thermal heat diffusion profile through the green roof layers.

For the experimental models tested in the laboratory, the heat exchange between the rainwater and the green roof material takes place during the first few minutes of the storm. The front is defined by movement of the infiltrating rain, and diffuses upstream and downstream, spreading its heat. For the experiment conducted, 10- to-15-min storms were not long enough to raise the green roof model temperatures more than 7.3 °F above room temperature. There is no radiation and little evapotranspiration; therefore, the conductivity of the green roof can be examined independently.

The IR photo shows how the green roof mitigates the temperatures on a black control roof by as much as 25 °F. The ponding of the control roof, for rain storms larger than the capacity of the drain is shown in the infrared photo. The black roof model has almost all temperatures in the 90s. The vegetated roof shows green and blue colours, signifying temperatures in the mid-70s. From the slope of the control roof and green roof hydrographs, the peak flows can be determined with $R^2$ larger than 0.9.

According to the NYC Department of Environmental Protection, green roofs can remove 35% of the total nitrogen in its inflow [22]. This study showed that wood mulch, when mixed in with soil, can effectively reduce nitrogen levels in soil runoff by an additional 17%, This provides evidence for the theory that incorporation of wood mulch into green roofs increases their usefulness as a mechanism for water quality improvement. There was no evidence found for the effect on pH. However, support was provided for the concept that soil temperatures will influence runoff temperatures, as well as the idea that green roofs are highly effective for inflow retention.

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