Retaining Stormwater
Northeast US

This document is a collection of abstracts with citations compiled by Drexel University highlighting research around green roofs' ability to retain stormwater in the Northeast United States. This is not a comprehensive literature review but is intended to be a first stop for a green roof researcher. These abstracts were compiled by Tenaya Hubbell-Wood and Korin Tangtrakul, under direction of Dr. Franco Montalto of Drexel University. Contact Korin for more information: krt73@drexel.edu

This document will be updated periodically to include the latest research. It was last updated in February 2020.

The Importance of green roofs and Sustainable development

Briza, L (2019) The Importance of green roofs and Sustainable development. Materials Science and Engineering. Vol 566. DOI: 10.1088/1757-899X/566/1/012003

The sustainable development is the observance to the principles of respect for nature, environmental protection and responsible approach to social and economic standards of urban development. Green roofs are an important and inherent aspect of such development. For current and especially future climate conditions they are also represent a signification factor of water management and are one of the ways to keep cities habitable for future generations as well. Green roofs can efficiently retain water and gradually release it back into the environmental in a place where was a driving rain without water affected site literally just flowed. The desired side effect of the process may be overall cooling of the environmental. Simultaneously, the vegetation constructions contribute to the elimination of the so-called heat island effect, and thus contribute to the natural change of water.

Water Quality Impacts of Green Roofs Compared with Other Vegetated Sites

Barr, Catherine M. & Gallagher, Patricia M. & Wadzuk, Bridget M. & Welker, Andrea L. (2017). Water Quality Impacts of Green Roofs Compared with Other Vegetated Sites. Journal of Sustainable Water in the Built Environment. Vol 3. Issue 3. DOI: 10.1061/JSWBAY.0000825

Green roofs are a convenient stormwater management strategy in highly developed, urbanized areas. Research has demonstrated that green roofs are effective at mitigating stormwater runoff volume, in addition to providing a range of other environmental benefits. Previous studies on the overflow from extensive green roofs have indicated that the overflow from these roofs, particularly those maintained with fertilizer, may contribute nutrients to nearby streams, storm sewers, and adjacent waterways. Whereas many studies have compared green roof nutrient concentrations with that of conventional roofs and urban streams, few studies have compared

green roof effluent with other vegetated systems' effluent. In this study, located in Villanova, Pennsylvania, green roof effluent was evaluated and compared with vegetated land uses (e.g., woods and grass) and other stormwater control measures (e.g., bioinfiltration rain garden and constructed stormwater wetland) typically found in urban watersheds. Effluent samples from all sites were tested and analyzed for concentration and mass loading of nitrogen (nitrate, nitrite, total Kjeldahl nitrogen, and total nitrogen) and phosphorus (orthophosphate and phosphorus). Overall, the green roof effluent concentrations for nitrogen and phosphorus species were statistically different than the other land uses, and often with higher concentrations. The green roof effluent was most statistically similar to the wooded land use. From a mass loading perspective, in terms of unit area of the contributing watershed, the green roof had a higher loading than the other land uses. However, the fertilized green roof exported less than 15 percent of the total input mass of nitrogen and phosphorus, demonstrating that volume reduction aids in managing the effluent.

Chemistry of Stormwater Runoff from a Large Green Roof in Syracuse, NY

Johnson, Alexander & Davidson, Cliff I. (2017). Chemistry of Stormwater Runoff from a Large Green Roof in Syracuse, NY. International Conference on Sustainable Infrastructure. DOI: 10.1061/9780784481196.005

A green roof can provide a wide variety of ecological benefits in urban environments such as reducing the amount of stormwater runoff. In addition, the growth medium may filter contaminated rainwater, providing runoff that is cleaner than the incoming rain. However, the growth medium might contribute other contaminants, thereby increasing the concentration relative to the rainwater. Thus, field experiments are needed to determine which contaminants are filtered out and which are leached from the growth medium during large rainstorms. It is also possible that some contaminants deposited from the atmosphere are picked up by the runoff.

To investigate these issues, we determined the chemistry of stormwater runoff from two adjacent rooftops: a 1.5 acre extensive green roof on the Onondaga County Convention Center and a similarly sized gray roof on the war memorial sports arena, both located in downtown Syracuse, New York. We assumed that the same atmospheric contaminants depositing on the green roof are also depositing on the gray roof. This allowed us to compare concentrations of chemical species in the rain, green roof runoff, and gray roof runoff to determine which contaminants are contributed by the rain, by leaching from the growth medium, and by atmospheric deposition. Results from storms sampled in 2014, 2015, and 2016 suggest that sulfate and copper are leached from the growth medium while lead is filtered. Additional experiments will be conducted to better understand the leaching potential of the green roof.

Long-term and seasonal hydrologic performance of an extensive green roof

Todorov, Dimitar & Driscoll, Charles T. & Todorova, Svetoslava. (2018). Long-term and seasonal hydrologic performance of an extensive green roof. SI Urban Hydrology. DOI: 10.1002/hyp.13175

Sustainable strategies such as green roofs have been implemented as stormwater management tools to mitigate disturbance of the hydrologic cycle resulting from urbanization. Green roofs, also referred to as vegetated roofs, can improve the urban landscape by reducing heat island effects, providing ecosystem services, and facilitating the retention and treatment of stormwater. Green roofs have received particular attention because they do not require acquisition and development of land and represent an application of biomimicry in design and construction. In this paper, we evaluate the effects of precipitation, evapotranspiration (ET), antecedent dry period (ADP), and seasonal variation on the run-off quantity and distribution of an extensive, sedum covered, green roof on a commercial building in Syracuse, NY, USA. The green roof greatly facilitated retention of precipitation events without significant changes over the 4-year study. The green roof retained on average 95.9 +/- 3.6% (6.5 +/- 5.6mm) per rainfall event, with a range from 75% to 99.6% (33.2 to 3.3mm). However, as precipitation quantity increased, the retention of water decreased. This high water retention capacity was the result of the combined effects of ET, stormwater storage (plants, growth media, and stormwater retention layer), and limited surface run-off from the roof deck due to variation in the sloping of the green roof and the tapered insulation to the deck drains. The water retention capacity of the green roof did not change significantly between growing and nongrowing seasons. Slightly greater precipitation during the growing season coincided with increased ET. Average potential ET during the growing season was approximately 3 times greater than during the nongrowing season. The hydrologic performance of the green roof was not significantly impacted by an ADP greater than 2days.

Storm Water Runoff Mitigation Using a Green Roof

Bliss, Daninel J. & Neufeld, Ronald D. & Ries, Robert J. (2009). Storm Water Runoff Mitigation Using a Green Roof. Environmental Engineering Science. Vol 26. Number 2. DOI: 10.1089/ees.2007.0186

A prototype green roof was constructed and monitored in Pittsburgh, Pennsylvania, to demonstrate a way to reduce storm water runoff and combined sewer overflow (CSO) events. The large impervious surface area created by urban development in Pittsburgh creates a wet weather flow that the existing combined waste waster and storm water sewer system cannot contend with. Green or vegetated roofs can reduce the amount of storm water that reaches the sewer conveyance system by replacing an otherwise impervious roof with porous soil that retains rainwater and plants that evapotranspire resulting in reduced storm water flows to the sewer system. The prototype green roof reduced the runoff volume by up to 70% compared to a conventionally ballasted roof covering a control portion of the same building. A reduction of at least 20% was found for rainfalls of 1.5 cm (0.60 inches) or less. The green roof also reduced the flow rate of runoff throughout storms. Peak values from the green roof were between 5% and 70% lower than control roof flow rates. For some small storms, the time of peak flow rate was delayed by up to several hours. In general, the green roof delayed the start of runoff and extended the time period of low residual flows that existed at the end of a storm. Water quality tests indicate that in most cases for the storms observed, a first-flush phenomenon was not evident in green roof runoff samples. Levels of phosphorus and chemical oxygen demand (COD) were elevated by the green roof. Both the control and green roofs produced runoff that demonstrated neutralization of slightly acidic rainfall.

Supporting Sustainable Service-System Design: A Case Study on Green-Roof Design with InDeaTe Template and Tool at Syracuse, New York

Acharya, Shakuntala & Ghadge, Kiran & Uchil, Praveen & Flynn, Carli & Johnson, Alexander & Squier, Mallory & Yang, Yige & Yang, Xiaoliang & Davidson, Cliff & Ameta, Gaurav & Rachuri, Sudarsan & Chakrabarti, Amaresh. (2017). Supporting Sustainable Service-System Design: A Case Study on Green-Roof Design with InDeaTe Template and Tool at Syracuse, New York. 19-33. DOI: 10.1007/978-981-10-3521-0_2.

InDeaTe Tool and Template is a sustainable design support, aimed at imbibing and improving the sustainability considerations in any design. This paper presents a case-study on 'design of green roof', a type of green infrastructure, to combat the existing issues of Stormwater Management in Syracuse. The primary objective of the design project is to design (or re-design) a green roof that will store stormwater for enough time during a reasonably strong storm so that the capacity of the Syracuse Metro treatment plant would not be exceeded. A second objective is to incorporate low environmental impact materials when designing the green roof so that the final design is more sustainable. The case study discussed in this paper, illustrates how the use of InDeaTe Tool not only improved sustainability considerations and led to many creative solutions, but could be used for design of more sustainable service systems.

Use of organic wastes to create lightweight green roof substrates with increased plant-available water

Xue, M. & Farrell, C. (2020) Use of organic wastes to create lightweight green roof substrates with increased plant-available water. Urban Forestry & Urban Greening. Vol 48. DOI: 10.1016/j.ufug.2019.126569.

Substrate design is important for stormwater retention and plant survival on green roofs. Green roof substrates are mostly inorganic, providing long-term stability, while organic components (<20% v/v) reduce substrate weight and increase water retention, depending on rate and type. Selection of organic components depends on availability and organic waste materials can improve sustainability and reduce costs. We aimed to use organic waste materials to create lightweight substrates with good aeration and increased plant-available water (PAW) to support plant growth on green roofs. We evaluated the effects of five locally available organic waste components (coarse coir, fine coir, composted green waste, almond hull, and pistachio shell) on the physical and chemical properties of a scoria-based substrate when added at 0, 5, 10, 15, and 20% by volume. We also examined their phytotoxic effects on plant growth using lettuce (Lactuca sativa) as bioassay species. Overall, higher rates (15–20 % v/v) of coarse coir, fine coir and composted green waste all reduced substrate weight and improved PAW. Pistachio shells and almond hulls reduced saturated bulk density but adversely affected plant growth, likely due to phenolic compounds. For the other amendments, rates above 10–15 % addition also decreased root and shoot growth in lettuce. This indicates a potential trade-off between water availability and growth in these substrates. Therefore, if a green roof needs to be amended to reduce weight but have improved PAW, coarse coir, fine coir and composted green waste would be the best choices.

Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems

Carson, T.B & Marasco, D.E. & Culligan, P.J. & McGillis, W.R. (2013). Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems. Environmental Research Letters. Vol 8. Number 2. DOI: 10.1088/1748-9326/8/2/024036

Green roofs can be an attractive strategy for adding perviousness in dense urban environments where rooftops are a high fraction of the impervious land area. As a result, green roofs are being increasingly implemented as part of urban stormwater management plans in cities around the world. In this study, three full-scale green roofs in New York City (NYC) were monitored, representing the three extensive green roof types most commonly constructed: (1) a vegetated mat system installed on a Columbia University residential building, referred to as W118; (2) a built-in-place system installed on the United States Postal Service (USPS) Morgan general mail facility; and (3) a modular tray system installed on the ConEdison (ConEd) Learning Center. Continuous rainfall and runoff data were collected from each green roof between June 2011 and June 2012, resulting in 243 storm events suitable for analysis ranging from 0.25 to 180 mm in depth. Over the monitoring period the W118, USPS, and ConEd roofs retained 36%, 47%, and 61% of the total rainfall respectively. Rainfall attenuation of individual storm events ranged from 3 to 100% for W118, 9 to 100% for USPS, and 20 to 100% for ConEd, where, generally, as total rainfall increased the per cent of rainfall attenuation decreased. Seasonal retention behavior also displayed event size dependence. For events of 10-40 mm rainfall depth, median retention was highest in the summer and lowest in the winter, whereas median retention for events of 0-10 mm and 40+ mm rainfall depth did not conform to this expectation. Given the significant influence of event size on attenuation, the total per cent retention during a given monitoring period might not be indicative of annual rooftop retention if the distribution of observed event sizes varies from characteristic annual rainfall. To account for this, the 12 months of monitoring data were used to develop a characteristic runoff equation (CRE), relating runoff depth and event size, for each green roof. When applied to Central Park, NYC precipitation records from 1971 to 2010, the CRE models estimated total rainfall retention over the 40 year period to be 45%, 53%, and 58% for the W118, USPS, and ConEd green roofs respectively. Differences between the observed and modeled rainfall retention for W118 and USPS were primarily due to an abnormally high frequency of large events, 50 mm of rainfall or more, during the monitoring period compared to historic precipitation patterns. The multi-year retention rates are a more reliable estimate of annual rainfall capture and highlight the importance of long-term evaluations when reporting green roof performance.

Assessing the Retention Capacity of an Experimental Green Roof Prototype

Da Silva, Mariana & Najjar, Mohammad K. & Hammad, Ahmed W. A. & Haddad, Assed & Vezquez, Elaine. (2019) Assessing the Retention Capacity of an Experimental Green Roof Prototype. Water. Vol 12. Issue 1. 195-204. DOI: 10.3390/w12010090.

Cities with high urbanization produce impervious areas. Drainage network overload results in recurring flooding. Much of the damage could be prevented through proper urban planning and good drainage practices. While Low Impact Development techniques have been known for several years, it is essential to encourage the association of this type of technology with conventional micro-drainage structures to increase rainfall runoff at the source where it is generated. Thus, the present work aims to analyze the efficiency of the use of the green roof technique in reducing the peak of the flow and the retention capacity when subjected to heavy rains at the building scale, and also explores its effects in tropical climatic zones with measurements during the summer and fall. The method used was experimental analysis of the Green Roof prototype with bromeliad’s at CESA-UFRJ, whose main results are the hydrogram of each rain event and the runoff coefficient for rainfall in the range of 100 mm/h and 150 mm/h.

A New Method to Determine How Compaction Affects Water and Heat Transport in Green Roof Substrates

Sandoval, Victoria & Suarez, Francisco (2019) A New Method to Determine How Compaction Affects Water and Heat Transport in Green Roof Substrates. Applied Sciences. Vol 9. Issue 21. 4697. DOI: 10.3390/app9214697.

Although compaction affects water and heat transport processes in porous media, few studies have dealt with this problem. This is particularly true for substrates, which are artificial porous media used for engineering and technological solutions, such as in vegetated or green roofs. We propose a methodology to study the effect of substrate compaction on the characterization of physical, hydrodynamic and thermal properties of five green roof substrates. The methodology consists in a parametric analysis that uses the properties of a substrate with known bulk density, and then modifies the substrate properties to consider how compaction affects water and heat fluxes. Coupled heat and water transport numerical simulations were performed to assess the impact of the changes in the previous properties on the hydraulic and thermal performance of a hypothetical roof system. Our results showed that compaction reduced the amplitude of the fluctuations in the volumetric water content daily cycles, increasing the average water content and reducing the breakthrough time of the green roof substrates. Compaction changes the thermal behavior of the green roof substrates in different ways for each substrate due to the dependence of the air, water and soil fraction of each substrate.

Influence of the Hydrogel Amendment on the Water Retention Capacity of Extensive Green Roof Models

Deska, Iwona Katarzyna & Mrowiec, Maciej & Ociepa, Ewa & Lewandowska, Agnieszka (2020). Influence of the Hydrogel Amendment on the Water Retention Capacity of

Extensive Green Roof Models. Journal of Ecological Engineering. Vol 21. Issue 1. 195-204. DOI: 10.12911/22998993/112763.

The goal of the research was to investigate the retention capacity of six green roof models (SHP1, SHP2, SHP3, SH, S, and SP) constructed with use of plastic garden trays, drainage elements Floradrain FD 25, filter sheets SF, and the extensive substrate. Models SHP1 and SHP2 were constructed in March 2017, models SHP3 and SH – in November 2017, and models S and SP – in April 2018. Models SHP1, SHP2, SHP3, and SP contained the plants (the goldmoss stonecrop). The substrates of Models SHP1, SHP2, SHP3, and SH contained the hydrogel amendment. The investigations were conducted with use of simulated (and partially natural) precipitations. The water retention capacity of each green roof model was established based on the difference between rain volume and the volume of runoff from model. The results show that green roofs can be useful stormwater management tools. The calculated stormwater retention rates ranged from 29.50 % to 85.15%. In most cases the best water retention capacity had model SHP3, constructed in November 2017 and planted in April 2018, containing substrate amended with superabsorbent (cross-linked potassium polyacrylate). The similarly constructed models SHP1 and SHP2, which were built in March 2017, in some cases have lower water retention capacity. These models contained older hydrogel and were overgrown with older, smaller, and worse looking plants, partially supplanted by mosses. Such results indicate that the efficiency of hydrogel may decrease over time. In many cases the models S (not vegetated, without hydrogel), SH (not vegetated, with substrate containing hydrogel), and SP (vegetated, without hydrogel) had slightly lower water retention capacity. The results of investigations indicate that there was a relatively strong positive linear correlation between retention depth and duration of antecedent period elapsed since preceding total (or substantial) saturation of green roofs (labelled in the paper as period since total saturation - PSTS). The weather conditions i.e. air temperature and relative permeability as well as PSTS are very important parameters that influence the retention capacity of green roof models. Result show that duration of PSTS can be stronger correlated with retention depth than antecedent dry period (ADP) elapsed since the end of last precipitation, regardless of its depth.

Quantifying Evapotranspiration from Urban Green Roofs: A Comparison of Chamber Measurements with Commonly Used Predictive Methods

Marasco, D.E. & Hunter, B.N. & Culligan, P.J. & Gaffin, S.R. & McGillis, W.R. (2014). Quantifying Evapotranspiration from Urban Green Roofs: A Comparison of Chamber Measurements with Commonly Used Predictive Methods. Environ Sci Technol. Vol 48. Issue 17. DOI: 10.1021/es501699h

Quantifying green roof evapotranspiration (ET) in urban climates is important for assessing environmental benefits, including stormwater runoff attenuation and urban heat island mitigation. In this study, a dynamic chamber method was developed to quantify ET on two extensive green roofs located in New York City, NY. Hourly chamber measurements taken from July 2009 to December 2009 and April 2012 to October 2013 illustrate both diurnal and seasonal variations in ET. Observed monthly total ET depth ranged from 0.22 cm in winter to 15.36 cm in summer. Chamber results were compared to two predictive methods for estimating ET; namely the Penman-based ASCE Standardized Reference Evapotranspiration (ASCE RET) equation, and an energy balance model, both parametrized using on-site environmental conditions. Dynamic chamber ET results were similar to ASCE RET estimates; however, the ASCE RET equation overestimated bottommost ET values during the winter months, and underestimated peak ET values during the summer months. The energy balance method was shown to underestimate ET compared the ASCE RET equation. The work highlights the utility of the chamber method for quantifying green roof evapotranspiration and indicates green roof ET might be better estimated by Penman-based evapotranspiration equations than energy balance methods.

Hydrological and thermal response of green roofs in different climatic conditions

Arkar, C & Domjan, S. & Majkovic, D. & Sumi, J. & Medved, S. (2019) Hydrological and thermal response of green roofs in different climatic conditions. Earth and Environmental Science. Vol 323. DOI: 10.1088/1755-1315/323/1/012063.

The paper presents a study on the thermal and hydrological response of lightweight extensive green roofs with lightweight mineral wool growing media in different European climate conditions. The green roof heat and mass transfer model was developed and experimentally validated. It was then integrated into a developed software tool for the whole year analysis of the green roof thermal and hydrological performance. The results of performed numerical analysis showed that heat losses in heating season and heat gains in summer months of the green roof is smaller compared to the reference non-vegetated roof in all considered climate conditions and depends on thickness of lightweight mineral wool growing media and especially on the green roof's irrigation scenario. The results of numerical analyses also demonstrated that the water retention of green roofs can be considerably improved if irrigation scenario considers the weather forecast. The weather forecast based green roofs´ irrigation also improves retention at stormwater events.

"PET tool" – a software tool for lightweight extensive green roofs performance analyses

Arkar, C & Domjan, S. & Majkovic, D. & Sumi, J. & Medved, S. (2019) "PET tool" – a software tool for lightweight extensive green roofs performance analyses. Earth and Environmental Science. Vol 323. DOI: 10.1088/1755-1315/323/1/012065.

Due to energy, environmental, and social benefits, green roofs are recognized as a bioclimatic technology and sustainable construction systems and are becoming a predominant solution in connection with urban planning and building envelope retrofitting. To support design and marketing of Urbanscape® lightweight extensive green roofs a special software tool was developed, which is presented in the paper. Performance evaluation tool (PET tool) is validated based on extensive and continuous 5-years in-situ monitoring of thermal and hydrological response of different Urbanscape green roofs. The key performance indicators of Urbanscape green roofs are evaluated based on calculated thermal and hydrological response. To emphasize the advantages of green roofs thermal response and performance indicators are determined also for non-vegetated roof for the same boundary conditions. PET tool enables i) evaluation of

Urbanscape green roofs' whole year thermal and hydrological response, ii) to search for the optimal design of the Urbanscape green roof system in terms of energy and water performance, iii) evaluation of comparative advantages compared to non-vegetated roof, iv) energy savings and CO2 emission reduction analyses for heating and cooling season. Analyses can be made for arbitrary worldwide climate conditions since meteorological parameters are gathered from Meteonorm database.

Hydrological and thermal regime of a thin green roof system evaluated by physically-based model

Skala, Vojtech & Dohnal, Michal & Votrubova, Jana & Vogel, Tomas & Dusek, Jaromir & Sacha, Jan & Jelinkova, Vladimira. (2020) Hydrological and thermal regime of a thin green roof system evaluated by physically-based model. Urban Forestry & Urban Greening. Vol 48. DOI: 10.1016/j.ufug.2020.126582

Green roofs, as an element of the green infrastructure, contribute to the urban heat island effect mitigation and the urban drainage outflow reduction. To achieve the desired functions, it is essential to understand the role of the individual roof layers and ensure their proper design.

A physically-based model was used to assess the hydrological and thermal regime of two experimental green roof test beds containing distinct soil substrates (a local Technosol and a more permeable commercial substrate “Optigreen”). The test beds together with a meteorological station were built on the building green roof. Each test bed has an effective area of one square meter and is equipped with a soil temperature sensor and an outflow gauge; one of the test beds is continuously weighed. The observed conditions were simulated using one-dimensional numerical model describing the water flow in variably saturated porous medium by Richards’ equation and the heat transport by the advection-conduction equation.

The model was able to satisfactorily reproduce the measured outflow and soil temperature. The water-potential-gradient based root water uptake module effectively captured the water storage depletion between the rainfall events. The difference between the two soil substrates tested is demonstrated by the contrasting ability of the soil layers to retain water. Model representation of the thermal conditions within the green roof soils was achieved using independently evaluated thermal properties of the soils and drainage board. The model was also used to analyze the effects of the substrate depth and type of vegetation cover on the transpiration and soil water regime of the green roofs. Increasing the substrate depth causes a rise of root water uptake and induces a significant reduction of the maximal temperature. The thinner soil profiles are more sensitive to the plant species selection.

Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance

Hakimdavar, Raha & Culligan, Patricia J. & Finazzi, Marco & Barontini. Stefano, & Ranzi, Roberto. (2014). Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance. Ecological Engineering. Vol 73. 494-508. DOI: 10.1016/j.ecoleng.2014.09.080

Green roofs offer many benefits for dense urban environments, one of which is their potential to supplement existing stormwater management infrastructure. The ability of green roof systems to act as a decentralized rainwater retention and detention network has been the topic of many recent studies. While these studies have provided important insight into the hydrologic performance of green roofs, none to date, to the knowledge of the authors, have specifically examined the effect of green roof drainage area on system performance in an urban climate. This research aims to understand how rainfall characteristics and green roof scale impact the peak and cumulative volume of green roof runoff during individual storm events. The performance of three extensive green roofs in New York City, each having the same engineered components and age but different drainage areas, is analyzed. It is found that green roof drainage area has the greatest impact on peak runoff reduction peak runoff reduction increases with increasing drainage area whereas rainfall retention and the time to peak runoff are not greatly influenced by drainage area. Data collected from the three green roofs are used to examine the applicability of a one-dimensional infiltration model, HYDRUS-1D, in predicting hydrologic behavior across the different green roof spatial scales. It is found that model performance improves as the green roof drainage area and rainfall volume increases. However, in general, HYDRUS-1D is only partially able to capture the hydrologic behavior of extensive green roofs across the different rooftop scales examined during this study.

Evaluation of common evapotranspiration models based on measurements from two extensive green roofs in New York City

Marasco, Daniel E. & Culligan, Patricia J. & McGillis, Wade R. (2015). Evaluation of common evapotranspiration models based on measurements from two extensive green roofs in New York City. Ecological Engineering. Vol 84. 451-462. DOI: 10.1016/j.ecoleng.2015.09.001

Although the evapotranspiration (ET) process has historically received limited attention, it is an important factor for assessing the health and behavior of urban green spaces, including green roofs. In this study, common potential evapotranspiration (PET) models, which assume non-water-limited substrate moisture conditions, and actual evapotranspiration (AET) models, which account for water-limited substrate moisture conditions, are used to predict ET from local climate conditions at two extensive Sedum green roof sites in New York City (NYC); one a vegetated mat system (termed W118) and the other a built in place system (termed USPS). Results from the predictions are compared to 12,000 h of on-site ET measurements obtained using a dynamic chamber system. Among the Hargreaves, Priestley-Taylor, Penman, and American Society of Civil Engineers Penman-Monteith PET models, results from the Priestley-Taylor model, which was developed to predict ET from a wet vegetated surface with minimal advection, best correlate with the dynamic chamber measurements (r-squared = 0.96 for W118, 0.82 for USPS). Nonetheless, a systematic error is seen whereby the Priestley-Taylor model overestimates the low ET fluxes observed during the winter months and underestimates the high ET fluxes observed during the summer months. This error is only exaggerated by the inclusion of an advective ET term. To estimate green roof ET under water-limited conditions, a storage model, antecedent precipitation index (API), and advection-aridity model are applied to the Priestley-Taylor formulation to calculate AET. Results indicate that only the API model, which is based on precipitation history alone, can improve upon the Priestley-Taylor PET predictions (r-squared = 0.96 on W118, 0.85 on USPS). Use of a more-physically based, substrate moisture storage greatly over-estimates ET reduction during dry periods. The work provides insight into which common ET models best capture the behavior of full-scale, extensive green roofs, and points to the need for better estimates of green roof ET under climate conditions typical of NYC's winter and summer months.

Green roof seasonal variation: comparison of the hydrologic behavior of a thick and a thin extensive system in New York City

Elliott, R.M. & Gibson, R.A. & Carson, T.B. & Marasco, D.E. & Culligan, P.J. & McGillis, W.R. (2016). Green roof seasonal variation: comparison of the hydrologic behavior of a thick and a thin extensive system in New York City. Environmental Research Letters. Vol 11. Number 7.

Green roofs have been utilized for urban stormwater management due to their ability to capture rainwater locally. Studies of the most common type, extensive green roofs, have demonstrated that green roofs can retain significant amounts of stormwater, but have also shown variation in seasonal performance. The purpose of this study is to determine how time of year impacts the hydrologic performance of extensive green roofs considering the covariates of antecedent dry weather period (ADWP), potential evapotranspiration (ET0) and storm event size. To do this, nearly four years of monitoring data from two full-scale extensive green roofs (with differing substrate depths of 100 mm and 31 mm) are analyzed. The annual performance is then modeled using a common empirical relationship between rainfall and green roof runoff, with the addition of Julian day in one approach, ET0 in another, and both ADWP and ET0 in a third approach. Together the monitoring and modeling results confirm that stormwater retention is highest in warmer months, the green roofs retain more rainfall with longer ADWPs, and the seasonal variations in behavior are more pronounced for the roof with the thinner media than the roof with the deeper media. Overall, the ability of seasonal accounting to improve stormwater retention modeling is demonstrated; modification of the empirical model to include ADWP, and ET0 improves the model R-2 from 0.944 to 0.975 for the thinner roof, and from 0.866 to 0.870 for the deeper roof. Furthermore, estimating the runoff with the empirical approach was shown to be more accurate then using a water balance model, with model R-2 of 0.944 and 0.866 compared to 0.975 and 0.866 for the thinner and deeper roof, respectively. This finding is attributed to the difficulty of accurately parameterizing the water balance model.

The Soil Water Apportioning Method (SWAM): An approach for long-term, low-cost monitoring of green roof hydrologic performance

Hakimdavar, Raha & Culligan, Patricia J. & Guido, Aida & McGillis, Wade R. (2016). The Soil Water Apportioning Method (SWAM): An approach for long-term, low-cost monitoring of green roof hydrologic performance. Ecological Engineering. Vol 93. DOI: 10.1016/j.ecoleng.2016.05.023
As cities increasingly adopt green infrastructure for the decentralized management of stormwater, there is a growing need to develop cost-effective approaches for the long-term monitoring and performance evaluation of these systems. In this study, a water balance approach - termed the Soil Water Apportioning Method (SWAM) - was developed to enable economic assessment of the long-term hydrologic performance of green roofs. SWAM provides estimates of green roof runoff and evapotranspiration (ET) based solely on measurements of local precipitation, substrate moisture, and the substrate maximum water storage capacity. To validate the approach, SWAM generated values of runoff and ET were compared with 30 months of runoff and ET data obtained from an extensive vegetated mat green roof located in New York City. Accurate runoff and ET estimates were obtained using as few as one substrate moisture measurement per day, although various other data logging frequencies were tested - with best results achieved with data logged every 6-24-h (Nash-Sutcliffe efficiency indices of 0.85-0.91 and 0.73-0.78, for runoff and ET respectively). SWAM-generated runoff values were further validated using 14 months of runoff data obtained at two other extensive green roof sites located in New York City, one a built-in-place system and the other a modular tray system. Results from this study indicate that SWAM provides a viable, low-cost approach for the citywide monitoring of green roof hydrologic performance with nominal instrumentation and implementation costs.

Evaluating growing media for a shallow-rooted vegetable crop production system on a green roof

Elstein, J. & Welbaum, Gregory & Stewart, D.A. & Borys, D.R. (2008). Evaluating growing media for a shallow-rooted vegetable crop production system on a green roof. Acta Horticulturae. 177-184. 10.17660/ActaHortic.2008.782.20.

Green roofs are roof tops planted with vegetation to beautify, modify temperatures, and reduce storm-water runoff to name a few of the reported benefits. Soil or potting mix are commonly used for green roof applications but may be heavy, difficult to contain, and leach mineral nutrients and particulates. The effectiveness of potting soil, petrochemical-based foam sheets and fiberglass sheets was compared on the roof of Seitz Hall on the Virginia Tech campus. In a randomized complete block design, four 4.88 x 0.61 x 0.21 in Plexiglas containers, subdivided into four 0.61 x 0.61 x 0.21 in subplots, were filled with 10 cm potting mix, foam, fiberglass, or blank control over a 6.8 cm drainage layer of gravel. Kale (Brassica oleracea var. acephala) was established from transplants grown from April through May. Runoff, roof temperature, mineral content, media composition, and biomass were recorded for each treatment. A gravity-fed irrigation system supplied water through drip tape as needed. The least runoff came from commercial potting soil and the most from foam. Fiberglass media had the greatest water holding capacity on a dry weight basis. Foam had high moisture holding capacity and good aeration that facilitated excellent root proliferation through the media. Fiberglass had a pH of 8.8 and less root growth. Potting soil produced the greatest kale biomass while foam was second. Foam and fiberglass bad lower nutrient content and cation exchange capacity compared to potting soil. The

mineral content and particulates in the runoff from fiberglass and foam media was very low. Alternative media, like fiberglass and foam, have potential but need to be refined and tailored to green roof applications.

Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models

Carson, Tyler & Keeley, Melissa & Marasco, Daniel E. & McGillis, Wade R. & Culligan, Patricia J. (2014). Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models. Ecosystem Services through Runoff Management. Vol 14. Issue 6. 589-603. DOI: 10.1080/1573062X.2015.1056742

To optimize the application of green roof technology, there is a need to quantify stormwater mitigation in advance of green roof construction. This study contributes toward meeting this need by assessing the utility of four hydrologic models for predicting green roof rainfall capture, including the: (1) curve number method, (2) characteristic runoff equation, (3) Hydrological Evaluation of Landfill Performance (HELP V3.9D) model, and (4) Storm Water Management Model (SWMM V5.1). Modeling results were compared to over twenty-four months of observed runoff data, collected between June 2011 and December 2013, from two full-scale green roofs in New York City (NYC). Both the curve number method and characteristic runoff equation had the highest Nash-Sutcliffe efficiency index (NSEI) between modeled and observed cumulative runoff depth per event (NSEI=0.97) due to parameter calibration requirements, where error was mainly due to variations in green roof antecedent moisture conditions. The HELP model was originally intended for evaluation of a continuous landfill cover. As a result, HELP's inability to account for the non-vegetated areas on green roofs caused underestimation of runoff depth for most events (NSEI=0.84). Alternatively, the SWMM model tended to overestimate event runoff depth (NSEI=0.94), thought to be the result of its storage term parameterization. Model assessments point to the need for more robust parameter estimation methods, particularly for inputs that are statistical or difficult to measure directly, to improve pre-development accuracy of green roof performance models.

Monitoring and Modeling the Long-Term Rainfall-Runoff Response of the Jacob K. Javits Center Green Roof

Abualfaraj, Noura & Cataldo, Joseph & Elborolosy, Yara & Fagan, Daniel & Woerdeman, Sloane & Carson, Tyler & Montalto, Franco A. (2018). Monitoring and Modeling the Long-Term Rainfall-Runoff Response of the Jacob K. Javits Center Green Roof. Water. Vol 10. Issue 11. DOI: 10.3390/w10111494

Drainage from the 27,316-m(2) Jacob K. Javits Convention Center (JJCC) green roof was investigated in the field to quantify the system's long-term rainfall-runoff response. The JJCC hosts one of the largest extensive green roofs in the United States. Utilizing four years of rooftop monitoring data collected using a weather station, custom designed and built drainage systems, three Parshall flumes equipped with pressure transducers, and weighing lysimeters, this study quantified the 25.4-mm-deep green roof's ability to decrease the volume and peak rate of runoff. With parameters derived from the site, the Environmental Protection Agency Stormwater Management Model (EPA-SWMM) predicted event total runoff volume and event peak runoff rates to within +10% to -20% and +25% to -15% of the observations, respectively. The analysis further indicated that approximately 55% of the cumulative precipitation that fell on the JJCC extensive green roof during the monitoring period (warm weather months, June 2014-November 2017) was captured and retained. The average percent retained on an event-basis was 77%, and average event runoff coefficient was 0.7, implying a substantial reduction in the volume and rate of runoff generated from the roof compared to the pre-green roof condition, when most, if not all, of the precipitated water would have immediately resulted in runoff. Our research suggests that, on average, 96% of rainfall events 6.35 mm or less were retained within the green roof, whereas 27% of the total event volume was retained for events greater than 12.7 mm in depth. A sensitivity analysis suggests if the substrate depth were increased, better stormwater capture performance would be achieved, but only up 127 mm, whereas increased precipitation coupled with warmer temperatures as a result of climate change could decrease the performance by up to 5%, regardless of substrate depth. An equivalency analysis suggested that even shallow green roofs can significantly reduce the required stormwater detention volume that New York City requires on new development. This particular green roof appears to be more than 18 times as cost-effective as a subsurface cistern would be for managing an equivalent volume of stormwater in Midtown Manhattan.

Observed and Modeled Performances of Prototype Green Roof Test Plots Subjected to Simulated Low- and High-Intensity Precipitations in a Laboratory Experiment

Alfredo, Katherine & Montalto, Franco & Goldstein, Alisha (2010). Observed and Modeled Performances of Prototype Green Roof Test Plots Subjected to Simulated Low- and High-Intensity Precipitations in a Laboratory Experiment. Journal of Hydrologic Engineering. Vol 15. Issue 6. DOI: 10.1061/(ASCE)HE.1943-5584.0000135

With continued urbanization pressure, regulators and developers alike are increasingly looking to new forms of green infrastructure and low-impact development technologies as a means of appropriately integrating built infrastructure into the landscape. This paper describes the results of a series of experiments designed to simulate the hydrologic performance of green roofs under variable precipitation conditions. The experiments were designed in order to test performance under both steady, low-intensity rainfall, as well as under short duration, high-intensity rainfall conditions. A control membrane roof and prototype green roofs of 2.5-, 6.3-, 10.1-cm depths were subjected to simulated precipitation in a laboratory setting. The green roofs delayed, prolonged, and reduced the peak rates of green roof discharge to 22-70% that of a standard roof surface, with greater percent reductions associated with deeper roofs. Negligible discharge was observed from all of the prototypes during the first 10 min of simulated precipitation. Although the fate of the 0.35 cm of precipitation that were applied over this time period can only be determined through additional controlled testing of the prototypes with shorter duration rain events, the potential significance of green roofs that retain this quantity of water is discussed in the context of the historical New York City precipitation record. The results also indicated that nearly all of the precipitation applied was discharged as drainage over the 24 h period immediately following the experiment, suggesting that the percentage of large storms that are retained in green roofs may be insignificant. Green roof runoff coefficients computed from an analysis of the discharge hydrographs ranged from 0.2-0.7, consistent with other studies. Two approaches to predicting the observed discharge using the U.S. EPA's Stormwater Management Model (SWMM) are also presented. The "storage node" approach achieves better overall predictions than the "curve number" approach, which itself tends to significantly underpredict discharge from these systems. Although reasonable sets of predictions were eventually obtained, the selection of appropriate model parameters would not have been possible without the availability of experimental data with which to calibrate the models. The experimental results support the argument that the storm water benefits of green roofs could be significant. However, the writers urge caution in interpreting the results of green roof drainage discharge calculations made using SWMM until additional calibration and validation attempts have been performed.

Modeling stormwater runoff from green roofs with HYDRUS-1D

Hilten, Roger Norris & Lawrence, Thomas Mark & Tollner, Earnest William (2008). Modeling stormwater runoff from green roofs with HYDRUS-1D. Journal of Hydrology. Vol 358. Issues 3-4. DOI: 10.1016/j.jhydrol.2008.06.010

A study was conducted on the effectiveness of green roofs to mitigate stormwater using computer simulation. In this study, the stormwater performance was simulated for a modular block green roof using a packaged soil moisture simulation, HYDRUS-1D, with simulation results verified by study site data. Simulations were run using HYDRUS-1D for 24-h design storms to determine peak flow, retention and detention time for runoff. Storm data collected as part of a green roof study in Athens, Georgia, USA were used to validate HYDRUS-simulated runoff. The study site consisted of a 37 m(2) (400 ft(2)) modular block green roof containing engineered soil and vegetation including several Sedum species. The study revealed that rainfall depth per storm strongly influences the performance of green roofs for stormwater mitigation, providing complete retention of small storms (<2.54 cm) and detention for larger storms, assuming the measured average moisture content (similar to 10%) as the antecedent condition.

Vegetated Roof Water-Balance Model: Experimental and Model Results

Sherrard, James A, Jr & Jacobs, Jennifer M. (2012). Vegetated Roof Water-Balance Model: Experimental and Model Results. Journal of Hydrologic Engineering, Vol. 17, Issue 8. DOI:10.1061/(ASCE)HE.1943-5584.0000531

A five parameter, daily vegetated roof water balance model (VR-WBM) was developed, calibrated, and validated by using experimental vegetated roof data from the Seacoast, New Hampshire region. The lysimeter experiment on a sedum canopy characterized water storage with a 0.051 mm resolution. Overall, the results show that the average stormwater runoff reduction was 32% for the study period, and an average reduction per storm was 57%. Average daily evapotranspiration (ET) rates were 1.24 mm/day during the warmest month and 0.52 mm/day during the coolest month. For well-watered conditions, the ET losses were well-modeled by using a grass reference evapotranspiration (ET) value with a crop coefficient of 0.53 for the study's sedum canopy in which the onset of stomatal closure occurs when the soil moisture is 0.11 m(3)/m(3). When soil moisture content values are lower than 0.11 m(3)/m(3), evapotranspiration rates decrease linearly with declining soil wetness. The VR-WBM does an excellent job predicting runoff (R-2 = 0.98) and storage (R-2 = 0.94). Although ET had a lower R-2 value, (R-2 = 0.59), the average ET values were within 3% of the observed values, and they do not appear to affect storage and runoff predictions. Additionally, the model demonstrated an ability to accurately quantify antecedent soil moisture and its effect on runoff generation.

Effects of Early Structural Changes of Engineered Soils on Green Roof and Bioretention Performance

Snehota, M. & Hanzlikova, J. & Heckova, P. & Sacha, J. & Jelinkova, V. & Kaestner, A. (2019) Effects of Early Structural Changes of Engineered Soils on Green Roof and Bioretention Performance. Earth and Environmental Science. Vol. 290. DOI: 10.1088/1755-1315/290/1/012086.

Engineered soils play an important role in urban hydrology e.g. in the functioning of green roofs and storm water bioretention beds. Water infiltration, colloid transport and heat transport are affected by changes in pore system geometry particularly due to development of macropores and clogging by particles. The rate of pedogenesis is often faster than in natural soils due to higher loads of particles as well as by extreme water regimes. In the presented project we assess the temporal changes of hydraulic properties of engineered soils in typical bioretention beds and green roofs by conducting field scale experiments. The aim is to elucidate changes in hydraulic properties by studying the structural changes of soils at the microscale by invasive and noninvasive methods. The outcomes of the research will lead to improved design and management procedures for green roofs and bioretention beds.

Assessment of a green roof practice using the coupled SWMM and HYDRUS models

Baek, Sang Soo & Ligaray, Mayzonee & Pachepsky, Yakov & Ahn Chun, Jong & Yoon, Kwang-Sik & Park, Yongeun & Hwa Cho, Kyung (2020). Assessment of a green roof practice using the coupled SWMM and HYDRUS models. Journal of Environmental Management, Vol. 261. DOI: 10.1016/j.jenvman.2019.109920

Green roof can mitigate urban stormwater and improve environmental, economic, and social conditions. Various modeling approaches have been effectively employed to implement a green roof, but previous models employed simplifications to simulate water movement in green roof systems. To address this issue, we developed a new modeling tool (SWMM-H) by coupling the stormwater management and HYDRUS-1D models to improve simulations of hydrological processes. We selected green roof systems to evaluate the coupled model. Rainfall-runoff experiments were conducted for a pilot-scale green roof and urban subbasin. Soil moisture in the green roof and runoff volume in the subbasin were simulated more accurately by using SWMM-

H instead of SWMM. The scenario analysis showed that SWMM-H selected sandy loam for controlling runoff whereas SWMM recommended sand. In conclusion, SWMM-H could be a useful tool for accurately understanding hydrological processes in green roofs.

Green roof substrate physical properties differ between standard laboratory tests due to differences in compaction

Conn, Richard & Werdin, Joerg & Rayner, John P. & Farrell, Claire (2020). Green roof substrate physical properties differ between standard laboratory tests due to differences in compaction. Journal of Environmental Management. Vol. 261 DOI: 10.1016/j.jenvman.2020.110206

Green roofs are expanding internationally due to the well documented benefits they provide for buildings and cities. This requires transferable knowledge of the technological aspects influencing green roof design, particularly substrate properties. However, this is made difficult due to differences in substrate testing methods referred to in green roof guidelines and standards. Therefore, we tested a green roof substrate using laboratory-based methods from European (FLL), North American (ASTM) and Australian (AS) green roof guidelines and standards to determine how these methods vary in characterising substrate physical properties (bulk density, water permeability and water holding capacity at field capacity (WHC)). Further, we compared the results from the laboratory-based methods with measures of bulk density and WHC in green roof platforms to determine whether standard methods accurately represent substrate properties in-situ. Results from the standard test methods varied due to differences in sample compaction. The standard test methods that employ Proctor hammer compaction (FLL and ASTM) had greater bulk density (at field capacity and dry) and lower water permeability than Australian standard methods that employ free-fall compaction. WHC did not differ among the standard methods. The Australian standard method better reflected bulk density at field capacity and WHC of the substrate under in-situ green roof conditions. For mineral based substrates, our results suggest that for the FLL and ASTM testing methods, a single Proctor hammer drop will produce a degree of sample compaction equivalent to the free-fall method (AS) and be more representative of bulk density in-situ. Subtle changes in testing procedures would allow for more direct comparison of substrate properties between standard methods and help enable the international transfer of knowledge for substrate design.

Design of a Remote-Controlled Platform for Green Roof Plants Monitoring via Hyperspectral Sensors

Moroni, Monica & Porti, Michele & Piro, Patrizia (2019) Design of a Remote-Controlled Platform for Green Roof Plants Monitoring via Hyperspectral Sensors. Water. Vol 11. Issue 7. ISSN: 2073-4441. DOI: 10.3390/w11071368.

The combination of an appropriate design and careful management of green infrastructures may contribute to mitigate flooding (stormwater quantity) and pollutant discharges (stormwater quality) into receiving water bodies and to coping with other extreme climate impacts (such as

temperature regime) on a long-term basis and water cycle variability. The vegetation health state ensures the green infrastructure’s effectiveness. Due to their remarkable spatial and spectral resolution, hyperspectral sensing devices appear to be the most suited for green infrastructure vegetation monitoring according to the peculiar spectral features that vegetation exhibits. In particular, vegetation health-state detection is feasible due to the modifications the typical vegetation spectral signature undergoes when abnormalities are present. This paper presents a ground spectroscopy monitoring survey of the green roof installed at the University of Calabria fulfilled via the acquisition and analysis of hyperspectral data. The spectroradiometer, placed on a fixed stand, was used to identify stress conditions of vegetation located in areas where drought could affect the plant health state. Broadband vegetation indices were employed for this purpose. For the test case presented, data acquired agreed well with direct observations on the ground. The analyses carried out showed the remarkable performances of the broadband indices Red Difference Vegetation Index (Red DVI), Simple Ratio (SR) and Triangular Vegetation Index (TVI) in highlighting the vegetation health state and encouraged the design of a remote-controlled platform for monitoring purposes.