

Hydrologic Functions of Green Roofs in New York City

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Background

Highly developed urban landscapes are less pervious to water than undeveloped areas. During storms, well-vegetated areas moderate the intensity and quantity of stormwater runoff within a watershed. The velocity of rainfall striking the ground is reduced by trees and other vegetation. Water intercepted by tree canopies is quickly evaporated back into the atmosphere while water on the soil is absorbed, as if by a sponge, to be released slowly into local streams. In a heavily urbanized area, rain falls with full force onto the ground, runs off from paved or

impervious surfaces almost immediately, and little area is available for recharge into the local groundwater. The net effects of urbanization can be flooding, and in areas that are served by combined sewers, the discharge of dilute sewage into local waters.

Combined sewer overflows (CSOs) occur when sewage and stormwater are discharged from sewer pipes without treatment. CSOs are a significant source of environmental pollution in New York, where approximately 80% of the city functions on a combined sewer system (Protopapas, 1999) and only ~60% of rainfall is collected and treated (NYCDEP, 2001). In a combined sewer system, sewage and stormwater flow through the same pipes to wastewater treatment plants (Figure 1). Each wastewater treatment plant serves an artificial drainage basin known as a sewage-shed; in New York City there are 14 sewage-sheds of varying size. Total capacity is 1.8 billion gallons and total dry weather flow is 1.5 billion gallons per day.

During dry weather, all sewage is treated before it is discharged from the treatment plant to the estuary. However, during wet weather, the amount of water in sewer pipes may increase 10 or 20-fold. To prevent this increased volume of water from overwhelming treatment plants, a regulated amount (twice the average dry-weather flow) is directed to the plants by regulators that intercept sewage at all major CSO discharge points. The balance of the dilute sewage is discharged to local waters.

Underground storage tanks are an example of an engineering approach that retains CSO discharge flows for later re-introduction to the sewer system. Other engineering approaches seek to redress the hydrologic balance of urbanized areas by restoring or replacing some elements of the natural system. These approaches, some of which are known as Low Impact Development, increase the permeability of areas in a sewage-shed so as to delay or prevent stormwater from discharging immediately to the sewer system.

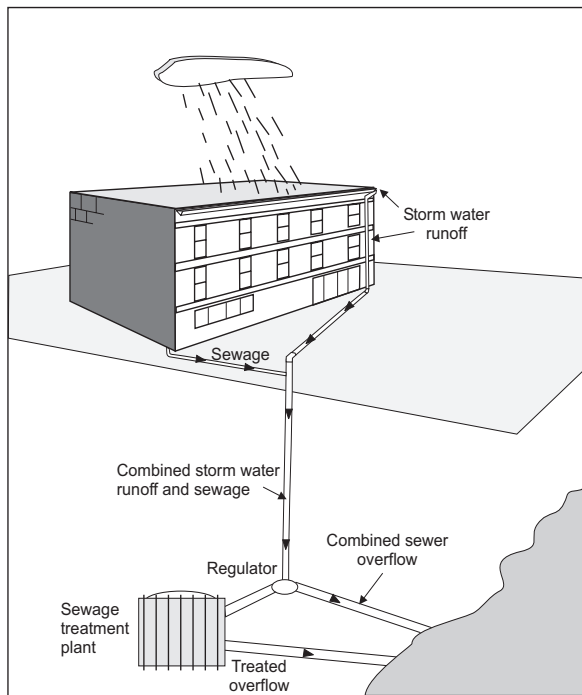


Figure 1. Combined sewer system. Note the regulator, which allows combined sewer overflows (CSOs) to occur when there is too much rain for the wastewater treatment plant to handle.

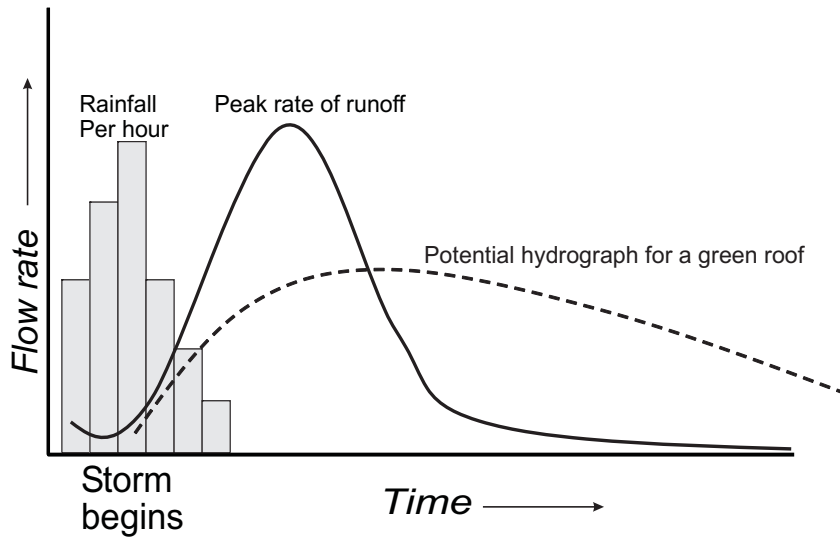


Figure 2. Hydrograph comparing hypothetical runoff from a standard roof to runoff from a green roof.

A 1999 report to the NYC Department of Environmental Protection (DEP) stated that vegetated roofs could have significant feasibility as an alternative to storage-tank technologies in some wastewater drainage basins (Copp et al., 1999). Modeling studies in Vancouver, BC; Seattle, WA; and Portland, OR have investigated this potential (Graham and Kim, 2003; Liptan et al., 2004; Taylor and Ganges, 2004). This study evaluates potential green roof hydrological functions through data analysis and modeling to determine whether green roofs could have an impact on the frequency and severity of combined sewer overflow events in New York City.

Green Roof Functions

Green roof infrastructure could benefit New York City by absorbing and later evaporating stormwater as well as retarding its flow. The overall effect would be a reduction in the amount and rate of discharge of stormwater into the combined sewer system, thus potentially reducing the frequency and volume of CSO events. Even small reductions in flow may have benefits that are much larger than expected to the extent that they reduce peak rates and flow volumes responsible for much of the flooding

and CSO events.

Studies have shown green roofs to be effective at capturing rainfall. For example, the city of Portland found that a green roof with a 4 – 5 inch (10 – 13 cm) growing medium and 72% plant cover of mixed succulents could absorb 69% of the annual rainfall that fell on it (Hutchinson et al., 2003). During summer storms, the roof retained 100% of the rainfall, and peak runoff rates were significantly lower for the green roof than for a control roof. For a theoretical

discussion of water relations on a green roof, see Appendix I.

The ability of green roof infrastructure to function as a stormwater catchment system depends on a number of factors including type of green roof (intensive or extensive), soil type, plant type, severity of a particular storm, and antecedent weather. The design of a green roof system needs to optimize both hydrological and structural functionality. For example, the



Figure 3. Case study areas.

lightweight, soil-like growing media used on extensive green roofs are designed to minimize load on weight-bearing roof structures, while still absorbing and storing rainwater. Choice of plant type also affects these functions. A common current choice for extensive green roof plants are desert-adapted stone crops (sedums), capable of withstanding both heat and drought. These plants are succulents, meaning that they have a high plant water-holding capacity; furthermore, they open their stomates at night to reduce evaporative losses (Raven et al., 1992).

While very heavy storms (e.g., several days of continuous rainfall) can lead to saturation and diminish the ability of green roofs to capture rainfall, rainwater still percolates through the green roof system before entering the sewer system, creating a moderate delay between peak rainfall and peak runoff from a green roof (Figure 2). Conversely, a prolonged drought could lead to soil compaction and reduction in green roof functionality. However, such compaction is less likely in the case of green roof soils than in regular soils, because green roof soils generally consist of large grains with many internal air spaces.

Climate Change

Global climate change presents significant challenges to the New York metropolitan region. Sea-level rise and accompanying increases in coastal storm flooding have been identified as a key vulnerability of the region (Rosenzweig and Solecki, 2001). Local tide-gauges show that sea-level is already rising, due in part to geological processes and in part to recent anthropogenic warming (Gornitz, 2001). Global warming and its accompanying projected rise in sea level are likely to lead to increases in the flooding damages that accompany coastal storms (Zhang et al., 2000; Senior et al., 2000; Gornitz, 2001). Individual rain events are also expected to increase in intensity (IPCC, 2001). Thus, the frequency of CSO discharges may rise as rising

sea levels diminish the sewers' conveyance capacity, while rainfall intensity grows.

Methods

Rainfall and runoff data from the Pennsylvania State University Center for Green Roofs Research (Penn State) were analyzed to determine the extent to which extensive green roofs are capable of capturing rainfall that would otherwise run off into the sewer system. The site is approximately 250 miles west of New York.

The data analysis was complemented by development of a simple simulation model (NYGRM/Hydro) that was used to conduct experiments regarding the impact of green roof infrastructure on stormwater runoff at the sewage-shed scale in NYC. A range of green roof performance inputs were tested, including those corresponding to the results of the data analysis.

The model was used to simulate captured runoff for two case studies, the Newtown Creek and North River sewage-sheds (Figure 3). Newtown Creek is the largest sewage-shed in New York City and includes parts of Manhattan, Brooklyn, and Queens. Upgrades to increase this plant's current capacity of 310 million gallons per day are being planned. The North River wastewater treatment plant serves Manhattan's West Side including Columbia University. The North River sewage-shed is approximately half the size of Newtown Creek, but has the same percentage of land surface area covered by flat roofs. The capacity of North River's treatment plant is 170 million gallons per day.

Data Analysis

The Penn State experimental design consists of six identical small buildings, three with standard roofs and three with extensive green roofs. The green roofs have a drainage layer, a 3.5 inch (8.89 cm) layer of expanded clay-based mineral substrate, and a mix of *Sedum spurium*, *Sedum album*, and *Delosperma nubigenum*,

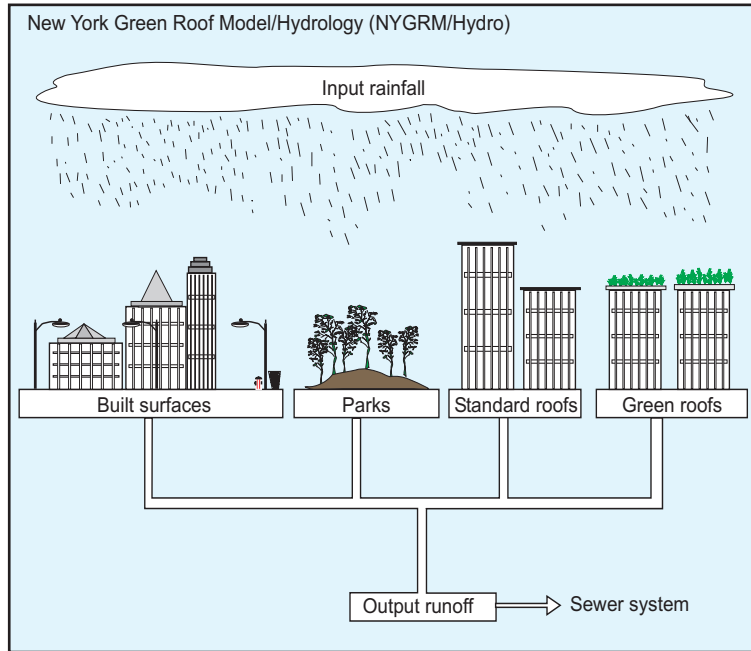


Figure 4. New York Green Roof Model/Hydrology (NYGRM/Hydro). Rainfall is the input and stormwater runoff is the output.

covering 90-100% of the surface. Each building is equipped with an enclosed gutter connected to a barrel with a pressure transducer to sense rainfall volume at 5-7 minute intervals. The experimental design also includes a weather station to collect meteorological data including rainfall at 5-minute intervals. Penn State data for June 2003 – September 2003 were used. Matched pair t-tests with unpooled variance were used to verify a significant difference at the 99% level between runoff from the standard roofs and runoff from the green roofs. Data from the three green roofs were averaged together, as were data from the three standard roofs.

Average captured runoff Average captured runoff (or retention) was defined as rainfall that makes direct contact with the roof but does not drain from the roof. It was calculated according to equation (1). Percent captured runoff (percent retention) was calculated according to equation 2.

$$\text{Average captured runoff} = \frac{[\sum_{i=1}^n (R_i \cdot r_i)]}{n} \quad (1)$$

$$\text{Captured runoff} = \frac{\sum_{i=1}^n (R_i \cdot r_i)}{\sum_{i=1}^n R_i} \quad (2)$$

Where R_i = total rainfall for event i
 r_i = total measured runoff for event i
 n = total number of rainfall events

Average captured peak runoff Because the green roof system retards (detains) the flow of stormwater, there can be a significant lag between the time a raindrop makes contact with the roof and the time it enters the sewer system. This is particularly important from a CSO reduction standpoint because it delays the time of peak runoff from the green roof. Peak rates of rainfall were computed based on the highest volume of rainfall that occurred in any five-minute period during each rainfall event.

Table 1. Baseline data for North River and Newtown Creek sewage-shed case studies.

Component	North River areas			Newtown Creek areas		
	(acres)	(km ²)	(%)	(acres)	(km ²)	(%)
Built surfaces	2,023	8.19	51	5,403	21.86	63
Parks	773	3.13	20	744	3.01	9
Standard flat roofs	1,135	4.59	29	2,451	9.92	29
Green roofs	Depends on greening scenario.					

Table 2. Performance assumptions and reservoir heights used in the box model. The Penn State scenario for flat roof and green roof rainfall capture correspond to results of the data analysis.

Component	Performance scenario (% rainfall captured)				Reservoir height	
	Low	Medium	High	Penn State	inches	cm
Built surfaces	2	2	2	2	0.04	0.1
Parks	80	80	80	80	1.57	4.0
Standard flat roofs	2	2	2	24	0.20	0.5
Green roofs	20	50	80	80	0.98	2.5

Note that the peak rainfall and the peak runoff for each roof may occur at different times.

Factor analysis The data were also analyzed using multiple linear regression to determine the degree to which the amount of runoff captured depends on the amount of rainfall and event duration, as well as antecedent conditions such as inter-event interval (measured in number of hours elapsed since the end of the previous rain event). Meteorological factors including relative humidity, solar radiation, and windspeed were also compared to runoff rates. For each of these factors, three-day averages were used. The meteorological variables were used as proxies for soil moisture, since soil moisture was not measured directly due to the incompatibility of soil moisture probes with green roof growing media. A determination of which factors best predict green roof retention capabilities can help to predict the hydrological effects of a severe storm in an area with green roofs with more accuracy.

**New York Green Roof Model/
Hydrology (NYGRM/Hydro)**

To determine the effect of green roofs on New York City hydrology, a simple green roof infrastructure stormwater model (New York Green Roofs Model/Hydrology (NYGRM/Hydro)) written in the C-sharp programming language was developed to simulate rainfall-runoff relationships at the sewage-shed level (Figure 4). The model treats the sewage-shed

as a large box filled with smaller compartments. Using GIS data, the land area within each case study was divided into built surfaces, parks, standard flat roofs, and green roofs (Regional Plan Association) (Table 1). Built surfaces include streets and structures without flat roofs.

Daily rainfall data from Central Park, NYC for 1984 (a wet year) and 1988 (a normal year) were used to drive the model. Total rainfall in 1984 was 57 inches (145.02 cm), and total rainfall in 1988 was 45 inches (113.53 cm). The model distributes rainfall among the compartments based on the percentage of the sewage-shed's total land area occupied by that compartment. The distribution of each compartment's total area is not considered, nor are edge or splatter effects.

The model was run with three greening scenarios – 0% (base case), 10%, and 50% adoption of green roofs in the sewage-sheds – and four roof performance scenarios (Table 2). The performance scenarios vary assumptions about the ability of standard flat roofs and green roofs to capture runoff. The high scenario uses green roof retention based on our Penn State findings (80% runoff-capture rate), but assumes that standard-roof retention is the same as built-surface retention. The medium scenario is in line with other studies that report green roof capture of approximately 50% of rainfall.

Each performance scenario assigns each compartment a unique homogeneous water-holding capability. Each compartment is

also assigned a reservoir height that specifies the maximum depth to which water can fill. This means that each compartment has the capability to retain some percentage of water, but there is a finite total amount that can be held. Once a compartment is saturated with water, the percent runoff captured falls to zero. (Evaporation was incorporated indirectly by programming each reservoir to empty after two days.)

The model calculates the total annual runoff for the sewage-shed. Percentage reductions in total annual runoff were calculated by dividing output for the greening scenario by output for the base case for each performance scenario and each year.

The performance scenario inputs are approximations because the ability of any surface to retain water is partially based on antecedent conditions. The ability of a surface to hold water gradually decreases as it becomes more saturated, as opposed to the sudden drop to zero absorption in the model. Furthermore, it is clear that all members within a single category will not retain water in precisely the same manner. However, the simulation experiments with the model can suggest the way parts of the system may behave in different rain events.

Results

Data Analysis

Analysis of the Penn State data showed that green roofs are effective at capturing (retaining) rainfall during rainstorms (Figure 5). On average, the green roofs captured 80% of the rainfall (Table 3). A hydrograph for runoff during a typical rain event at Penn State is shown in Figure 6. Between June and September 2003, the green roofs captured more rainfall than the

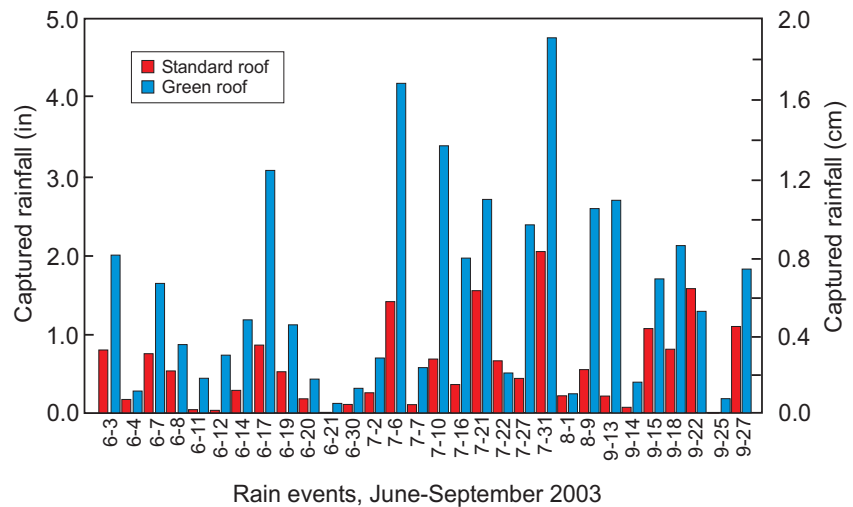


Figure 5. Captured runoff, June–September, 2003.

Table 3. Captured runoff as a percentage of rainfall on standard roofs and green roofs at Penn State Center for Green Roofs Research, June–September, 2003.

Captured runoff	Standard roof		Green roof	
Average runoff captured (% of rainfall)	24		80	
Peak runoff captured (% of rainfall)	26		74	
Captured runoff (inches and cm)	inches	cm	inches	cm
Average runoff captured	0.22	0.57	0.58	1.49
Peak runoff captured	0.03	0.08	0.06	0.16
Peak runoff extremes (inches and cm)				
Maximum peak runoff	0.18	0.46	0.11	0.27
Minimum peak runoff	0.01	0.02	0.00	0.00

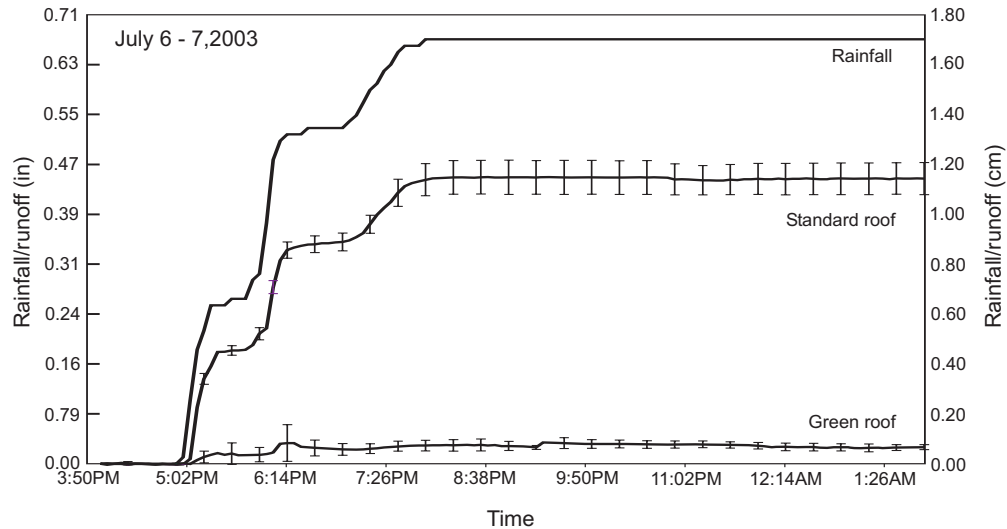


Figure 6. Simulated runoff, July 6–7, 2003.

standard roofs during all but two of the rain events and in these two cases, the difference was 0.04 inches (0.1 cm) or less. A comparison of standard roof runoff minima and green roof minima showed that the standard roofs always had at least a small amount of runoff, whereas the green roofs sometimes had no runoff. At peak times, the green roofs captured 74% of the rainfall.

The factor analysis showed that total rainfall is the best predictor of captured runoff for a rain event. Adding inter-event interval, peak rainfall, and a three-day solar radiation average improved the adjusted r^2 from 0.45 for rainfall alone to 0.56 with the inclusion of the additional factors. Predicting runoff capture as a percent of total rainfall was more difficult. The adjusted r^2 for rainfall alone was 0.34; adding additional factors produced an r^2 of 0.52. Equations (3) and (4) show the final multiple regression equations.

$$\text{Captured runoff (inches or cm)} = 0.243 \cdot R + 0.002 \cdot i + 0.128 \cdot p + 0.002 \cdot s - 0.230 \quad (3)$$

$$\text{Captured runoff (percent)} = -0.123 \cdot R + 0.002 \cdot i - 0.004 \cdot d - 0.011 \cdot h + 1.64 \quad (4)$$

- Where R = total rainfall (inches or cm)
- i = inter-event interval (hours since end of previous rain event)
- p = peak rainfall (highest 5-minute rainfall volume during event)
- s = solar radiation (three-day average watts/m²)
- d = event duration (hours)
- h = relative humidity (three-day average %)

NYGRM/Hydro Simulations

Simulations showed that green roofs could reduce annual stormwater runoff at the sewage shed level by as much as 10% in North River and 9% in Newtown Creek with 50% green roof infrastructure (Table 4). For both case studies, 10% green roof infrastructure produced at most a 2% reduction in runoff from the base case. In general, increasing the infrastructure from 10% to 50% reduced runoff by as much as 8 additional percentage points for the high performance scenarios. Changing from a low performance scenario to a high-performance scenario reduced runoff by as much as 7 additional percentage points. The simulations consistently showed differences of less than 0.5% between the wet year and the normal year,

Table 4. Model results for North River and Newtown Creek sewage-sheds using Central Park meteorological data for 1988 (normal year) and 1984 (wet year) with 10% and 50% greening scenarios. 0% represents the base case with 0 green roofs.

Runoff (% of base)	North River 1984			North River 1988			Newtown 1984			Newtown 1988		
	0%	10%	50%	0%	10%	50%	0%	10%	50%	0%	10%	50%
Greening Scenario →												
Performance Scenario												
Low (%)	100	99	97	100	99	97	100	99	97	100	99	97
Medium (%)	100	99	93	100	99	93	100	99	94	100	99	94
High (%)	100	98	90	100	98	90	100	98	91	100	98	91
Penn State (%)	100	98	92	100	98	92	100	99	93	100	99	93

with slightly better performance in the normal year. Overall, the effect of green roofs was slightly more pronounced in retaining runoff in North River than in Newtown Creek.

Discussion

Analysis of Penn State data showed that extensive green roofs are effective at capturing rainfall. The green roofs captured 74% of the peak rainfall, implying that green roofs can reduce the sudden influx of water that causes CSOs. A green roof, in effect, acts as capacitor for the sewer system, dispensing water at a moderated rate that presents less strain to the design of the system and fewer opportunities for overflow.

The data also showed that standard roofs captured 24% of rainfall on average, although the small Penn State roofs may be subject to larger edge effects, with the likely result that water is splattering over the sides of the roofs rather than being captured. There should be comparatively less splatter from the green roofs because the soil medium is absorbent. A runoff capture rate of 80% for the green roofs is still possibly an overestimate. On the other hand, summer 2003 was a particularly wet summer in Pennsylvania, suggesting that the green roofs performed well when needed most and that their performance might be even better in less wet years.

Green roofs are complex systems with

varying capacities for retaining rainwater and retarding runoff. When a range of capture rates (including 80%) was tested in the NYGRM/Hydro model, the box model results indicate that extensive green roofs can retain up to ~10% of annual rainfall at the sewage-shed scale, given the 50% adoption rate. Depending on the pattern of rainfall and the volume of runoff required for a CSO to occur, small reductions in runoff could translate into larger CSO reductions.

Conclusions

The research presented indicates that green roofs, as a means of runoff source prevention, show promise for reducing the frequency of CSO discharge in urban areas like New York City. Our data analysis and model simulations showed that green roofs have the potential to be effective in reducing runoff at the individual building and sewage-shed scales. The research also indicates that a significant percentage (~50%) of roofs in a sewage-shed would need to be greened to significantly lower the frequency and severity of CSO events. Analysis of the Penn State data showed that individual extensive green roofs can capture up to 80% of rainfall. Simulations of the impact of green roof infrastructure in New York indicated that 50% green roof infrastructure in a sewage-shed could produce up to a 10% reduction in runoff. Therefore, it appears that, if adopted at the

sewage-shed scale, green roof infrastructure could potentially provide an effective stormwater catchment system and could help to prevent combined sewer overflow events.

As climate changes and sea level continues to rise, low-lying storm sewers may have increasing trouble discharging CSOs, with the possibility of combined sewage backing up in pipes and rising to street level. The development of effective stormwater catchment systems, such as green roofs at the sewage-shed scale, is therefore of particular importance in coastal areas such as New York City that are likely to be affected by climate change.

Further Research

Understanding the role of environmental factors in green roof performance is needed in order to optimize their water-retention capabilities based on the region's climate. We recommend that further research be conducted to determine more accurately the potential impact of green roof infrastructure on combined sewer overflow events in New York City. This additional research would involve collection of better data regarding both the within-hourly distribution of rainfall occurring in this region and the type of rainfall events that cause CSO discharge in each of the City's sewage-sheds and sub-sewage-sheds. More data also need to be collected quantifying the rates of runoff generated on green roofs of different sizes and configurations under rainfall events of different intensities and duration.

More detailed hydrologic models could then be used to establish more precise estimates of the extent of green roofs that would potentially need to be introduced to the urban land-

scape to achieve quantifiable reductions in CSO discharge. The NYGRM/Hydro simulates runoff, not reduction in CSO volume; more complex models are needed to simulate the impact of green roofs on CSO volume directly. The EPA SWMM model, in combination with local data on green roof performance, is one model that might be used to begin to directly address the relationship between green roofs and CSO events (Figure 7). The SWMM model has the advantage of a more direct inclusion of evaporation as well as the ability to treat each regulator basin individually and then to aggregate up to the sewage-shed scale. The modeling effort could include refining inputs, evaluating the performance of a range of green roofs including both extensive and intensive systems, and testing the sensitivity of the model to different performance inputs and antecedent conditions.

Further research could also usefully explore the potential for other runoff source prevention techniques (e.g., rainwater harvesting, stormwater infiltration, etc.) as ecological infrastructure.

Acknowledgements

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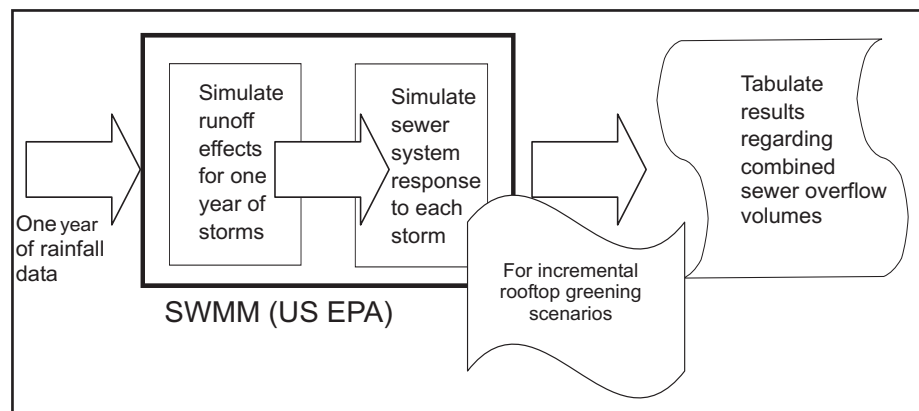


Figure 7. Diagram of green roof simulations with the EPA Stormwater Management Model

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