**Literature Review**

A representative sampling of studies of green roof stormwater benefits is summarized below.

Berghage, R., C. Miller, B. Bass, D. Moseley, and K. Weeks. 2010, Stormwater Runoff form a Large Commercial Roof in Chicago. Proceedings Cities Alive Conference. Vancouver, Canada. Nov 30-Dec 3.

* 150,000 square foot (1.39ha) roof was “purpose-built by Walmart to facilitate a quantitative evaluation of the relative performance of a membrane roof and an adjacent vegetated green roof.”
* 3 year monitoring study – “daily flow data from 2007and 2008 and 15 minute flow data from 2009 included over 100 precipitation events”
* The 75,000 s.f. extensive green roof was installed with “a low-transmissivity uniaxial drainage mat augmented with perforated conduit, 3 inches (7.6cm) of media and a Sedum groundcover. The green roof was not irrigated. The 1 inch (25 mm) drainage mat was fabricated from particles of post-industrial closed-cell polyurethane foam. The media properties were consistent with recommendations for multi-layer extensive media based on FLL. Plants, established from cuttings and seed, include varieties of Sedum, Dianthus, and Petrorhagia.”
* “The other half of the roof is a standard white 60-mil reinforced white PVC membrane.”
* The average retention for the green roof in the 106 precipitation events monitored between between 4 August, 2007 and 30 July 2009, was 74%.
* “Measured media moisture storage capacity was similar to preconstruction estimate based on standard media tests. Measured total media storage capacity of this 3” (7.6cm) media depth roof was about (50% by volume) 1.5” (3.8cm) or about 9375ft3 (265m3) and 70,129 gal (265,470L).”
* “Moisture storage capacity of the roof was greatest in the winter and decreased throughout the growing season… The ability of a soil to retain water can vary greatly with the prior moisture content of the soil and the nature of the wetting and drying cycles (hysteresis). The seasonal variation and range of moisture content observed in this study likely reflect the hysteretic behavior of soil moisture content in this media. This observation has some interesting implications for green roofs. It suggests one reason for the observed retention of additional rain on a roof already wet from an earlier event. It also suggests that in the summer the roof, even though more effective due to evapotranspiration, may be able to store less total water than in the winter or spring. The increase in maximum water retention observed on this roof in the winter means that the roof will be heavier in the winter at maximum field capacity than in the summer. For this roof the added water weight would be about 234,161 pounds (106,213kg) or about 3 pounds (per square foot (14.6kg/m2.”
* “Total measured daily rain retention greatly exceeded the media storage capacity in some of the larger and longer measured rain events suggesting that other moisture storage components like plant interception and tissue storage, evaporation during the rain event and transient storage in the drainage layer may play an important role in roof storm water retention for some events.”
* “Peak flows were reduced to an average of 35% of the precipitation peak and time to peak was delayed by a minimum of 1 hour and 15 minutes, comparing favorably to the pre-construction Time to Concentration estimate of 55 minutes.”
* “The average maximum Volumetric Water Content (VWC) for the roof for the period between June 2007 and June 2009 was 46%, with a maximum of about 60%. The maximum volumetric water holding capacity for this media determined by the Penn State AASL (Agricultural Analytical Services Lab) using the ASTM/FLL (ASTM, 2005; FLL, 2002) standard testing procedure prior to installation on the roof was 49.6% and the total pore volume was 58.6%. The *data obtained from the roof are thus in substantial agreement with the results of the apriori medium tests*. As might be expected the observed *maximum water holding capacity of the media was much lower during the establishment period* from October 2006 through May 2007. The average capacity of the medium during this period was 29% by volume or a maximum capacity of 0.87” (2.2cm) (Figure 5) compared to 1.5” (3.8cm) predicted by the ASTM media test and observed on the roof in data recorded between June 2007 and June 2009 (italics added).”
* “As with other green roof studies peak flow attenuation varied with rain event (Figure 8) however *peak reductions in this study of a very large roof were both more consistent and larger than those reported in studies of smaller roofs* (Berghage, et al, 2009). Peak attenuation was negatively related to storm duration (R2 =.58) (Data not shown). Attenuation was greatest for short storms and was less for longer storms (italics added)”
* “Time to peak was significantly affected by the storm intensity with *longer delays in some of the less intense storms observed* (italics added).”

Magnuson Klemenic Associates. 2007. Technical Memorandum: Stormwater Control Potential for Seattle Green Roof Retrofits. Seattle Public Utilities Green Roof Retrofit Study.

* “Green roof with a granular drainage system could increase the equivalent time-of-concentration of the roof by over 1500% compared to a green roof with a drainage layer that does not impede flow that has percolated through the roof.”
* Simulated effectiveness of green roofs at mitigating Seattle storms and found: “Expected peak rate reduction during wet-season design storms is less than 10% for multi-course green roofs with a drainage board/mat, which currently are the most typical assembly used in the US. Adding a granular drainage layer may improve the performance to approximately 33 to 50% rate reduction.”

Berghage, R.D., D.Beattie, A. R. Jarrett, C. Thuring, F. Razaei, T. P. O’Connor. 2009. Green Roofs for Stormwater Runoff Control. National Risk Management Research Laboratory Office Of Research And Development U.S. Environmental Protection Agency Cincinnati, OH 45268. EPA/600/R-09/026. Downloaded from [www.epa.gov/ord](http://www.epa.gov/ord)

* “Stormwater runoff was monitored and analyzed from January, 2005 through November, 2005. Replicated data were collected for 72 precipitation events from three green roofs and two flat asphalt roofs.”
* “These data confirm previous data from other studies’ conclusions that a 3.5 - 4 in. (8 - 10 cm) deep green roof can retain 50% or more of the annual precipitation.”
* “Flow rates were reduced in runoff from green roofs until the systems were saturated at which point runoff flow roughly equaled the rate of precipitation input.”
* Evaluated evaporation and evapotranspiration using weighing lysimeters planted with a mixture of Delosperma nubigenum and Sedum album vs unplanted ones with green roof media and drainage geotextile. Drying cycles lasted 21 days. Green roof plants lost water rapidly following irrigation, after which they reduced water loss rates.
* “Evapotranspiration (ET) rates from green roofs were similar to other measured systems and could be described using normal ET prediction equations such as Pennman-Monteith. Unplanted media lost water at a similar rate initially but water loss declined below that of the green roof after a couple of days. Plants are thus essential to the system and move water from down in the media to the surface quickly, resulting in faster return of the retention potential for the green roofs.”
* “Green roofs retained over 50% of total precipitation during the study period. During the summer months, nearly 95% of the precipitation was retained. During winter, retention was smaller (<20%) and not significant.”
* “Rapid peak flows, i.e. high-intensity, short duration rainfalls were attenuated more than lower intensity, high-total volume longer period flows.”

Bengtsson, L., Grahn, L., Olsson, J., 2005. Hydrological function of a thin extensive green roof in southern Sweden. Nordic Hydrol. 36 (3), 259–268.

Studied the runoff from and the water balance of a thin extensive green roof with sedum-moss with 3 cm depth of growing medium, underlain by a thin drainage layer and found:

* “The annual runoff is rather close to that of natural river basins.”
* “Runoff is initiated when the soil is at field capacity, which for the studied roof corresponds to 9 mm storage.”
* “After that, on a not very short time basis, the runoff equals the precipitation.”
* “The reduction of the daily runoff can be described in a simple way knowing the daily precipitation, potential evaporation and storage capacity of the green roof.”
* Storage on the roof could exceed maximum storage capacity during more intense rain events.

Voyde, E., Fassman, E., Simcock, R., and Wells, J. (2010). ”Quantifying Evapotranspiration Rates for New Zealand Green Roofs.” J. Hydrol. Eng. 15, SPECIAL ISSUE: Low Impact Development, Sustainability Science, and Hydrological Cycle, 395–403.

* “Sedum mexicanum (Mexican stonecrop) and Disphyma australe (New Zealand iceplant) in a New Zealand designed, pumice- and zeolite-based substrate were analyzed to determine daily and hourly ET rates under both water-abundant and drought-stressed conditions.”
* “Water loss, and thus storage recovery of the substrate, was greatest in the first 9 days.”
* “Transpiration (T) by S. mexicanum contributed up to 48% of total ET (2.19 mm/day) and D. australe contributed up to 47% of total ET (2.21 mm/day).”
* “After the initial rate of rapid water loss, plants conserved water and ET was not significantly different from evaporation (E) from unplanted substrate.”

Fassman, E. and Simcock, R. (2012). ”Moisture Measurements as Performance Criteria for Extensive Living Roof Substrates.” J. Environ. Eng., 138(8), 841–851.

doi: 10.1061/(ASCE)EE.1943-7870.0000532

Found that:

* “laboratory measure of stress water plus readily available water is not statistically different from the field-measured retention for any storms with a minimum equivalent depth to the laboratory measure.”
* “while the FLL maximum water capacity metric provides a conservative estimate for typical structural loading when the substrate is wet (plants and other system elements must also be included), it should not be used to predict storm-water retention.”

Rezaei, F., A.R. Jarrett, R.D. Berghage, D.J. Beattie. 2005. Evapotranspiration Rates from Extensive Green Roof Plant Species. ASAE Meeting Presentatin Paper Number 052150. Written for presentation at the 2005 ASAE Annual International Meeting Sponsored by ASAE, Tampa Convention Center. Tampa, FL 17-20 July 2005.

* Study conducted in greenhouse at Pennsylvania State University on green roof planter boxes with 3.5 inches of growing medium.
* “Greenhouse controlled environmental conditions were used to measure and predict ET from CAM plants during winter and fall/spring regimes, along with climatic parameters including air temperature, wind speed, radiation and humidity during 21-day periods without rain.” Because ET is highest when soils still have considerable moisture, eg. in the first 5 days after a rain event in Berghage et al 2007, and in the first 9 days after a rain event in Voyde et al 2010, ET rates are expected to be lower in this study because soils were allowed to dry down for 21 periods without rain. In a study of woody species at grade, Sinclair et al (2005) found:
* ranspiration was unaffected by soil drying until the initial estimated transpirable soil water fraction had decreased to between 0.23 and 0.32 of that at field capacity.
* Beyond this point, transpiration rate declined linearly with available soil water fraction until reaching one fifth the rate observed in well watered plants.
* With further soil drying, the relative transpiration rates remained between 10 and 20% of that observed in well watered plants.
* “ET for a green roof with CAM plants averaged 0.61 mm/d and 1.12 mm/d for each dry day during the winter and spring/fall season, respectively.” These numbers are considerably lower than those found by Voyde et al, 2010 2.19 mm/day and 2.21 mm/day for Sedum mexicanum and D. australe. One reason the Rezaei et al ET rates are likely lower is because they allowed soil to dry down for 21 day periods, and ET rates are higher right after a rain event than after soil dries down (see second bullet above).
* “The planted boxes evapotranspired 28% and 57% more water to the atmosphere than was evaporated from the unplanted boxes for the winter and spring/fall, respectively.“
* “The original Penman equation and Penman-Monteith ET models explained the observed ET rates very well with crop coefficients of 0.74 in winter and 1.97 in fall/spring.”

Berghage, R. D., A. R. Jarrett, et al. (2007). Quantifying Evaporation and Transpirational Water Losses from Green Roofs and Green Roof Media Capacity for Neutralizing Acid Rain. National Decentralized Water Resources Capacity Development Project, Penn State University.

* Compared green roof modules planted with drought tolerant succulent species to unplanted modules.
* “When water was readily available the plants used it at a relatively rapid rate compared to evaporation from the media of the control roof modules. As water became more limiting, the water loss rate of the planted modules was reduced to a rate not significantly different than the unplanted modules.”
* “The affect of plants is thus greatest for the first 5 days or so following a rain event when the plants essentially double the rate of recharge of the media moisture holding capacity allowing more of the next rain event to be stored and less to run off.”
* Water loss during the day when water was readily available followed the expected pattern for ET (Larcher 1995) with water use exceeding evaporation in the morning or early afternoon, reduced relative to evaporation or equal to evaporation during the heat of the day and higher again in the evening.
* “…the contribution of plants to green roof stormwater management potential is largely a function of rain event size and interevent interval.”
* “The relative contribution of the plants to the stormwater function of a green roof is greatest (approximately 40% of the total stormwater retention response in this study) in areas with relatively frequent, relatively small rains.”

Carpenter, D.D., Kaluvakolanu, P. 2011. Effect of roof surface type on stormwater run-off

from full-scale roofs in a temperate climate. Journal of Irrigation and Drainage

Engineering 137:161-169.

* Compared runoff from 153 m2 asphalt, 84.7 m2 gravel ballasted, and 325.2 m2 extensive green roofs.
* Planted 2005 with 7 species of Sedums, irrigated for 2 years, then irrigation was discontinued.
* 10.16 cm deep growing medium with less than 6% organic matter by weight.
* Longest green roof flow path: 20.7 m
* Green roof slope (V:H): 1:24
* Water quantity results:
* Monitored April through September 2008, total of 21 rain events
* Green roof rainfall retention varied, from 99.45% rainfall retention in August to 34.66% for September. Attributed variability to rainfall intensity/frequency/duration, evapotranspiration rates, and initial soil moisture.
* Time delay between when rainfall begins and when the green roof exhibits measurable runoff varied from several minutes to several hours, depending on rainfall characteristics and media saturation.
* Water quality results:
* Monitored 5 water quality events with rainfall greater than 1.27 cm in a 24 hour period.
* “There was significant variability between rainfall events, and the nutrient removal and water quality performance of the investigation is inconclusive. However, the data provide some indication that a green roof could be effective at reducing nutrient and solid loadings.”
* See Task 9 for P and TSS results
* Nitrate:
* Gravel roof had highest nitrate concentrations; green roof had higher mean nitrate concentrations compared to asphalt roof but the difference was not statistically significant - BUT green roof had much less volume of runoff.
* Mean mass was lower for the green roof than for the asphalt roof, but higher for the green roof than the gravel roof. Mass per unit area was lowest for the green roof: green roof = 0.00212 g/m2 nitrate; stone roof 0.00366 g/m2 nitrate; asphalt roof 0.00569 g/m2 nitrate).