**Summary of Green Roof Water Quantity Benefits**

Many studies have shown that, compared to traditional hard roofs, green roofs:

1. decrease runoff peak discharge (eg. Berghage et al 2010, Carter and Rasmussen 2006)
2. delay peak runoff (eg. Carter and Rasmussen 2006, Van Woert et al 2005, Berghage et al 2010)
3. reduce runoff volume (eg. Carter and Rasmussen 2006, Teemusk and Mander 2007, Van Woert et al 2005)

Green roof stormwater performance is affected, for example, by regional climatic conditions, storm size, rain intensity, frequency, and duration, antecedent moisture in the soil, transmissivity of drainage layer, vegetation species and diversity, length of flow path, roof size, growing medium composition and depth, and roof age.

For small rainfall events (typically less than ½ inch) little or no runoff will occur (e.g. Rowe et al 2003, Simmons et al 2008, Moran et al 2005). Lower intensity storms also result in greater stormwater retention than high intensity storms (Villarreal and Bengtsson 2005).For storms of greater intensity and duration, a vegetated roof can significantly delay and reduce the runoff peak flow that would otherwise occur with a traditional roof.

Annual runoff volume reduction in northern temperate regions is regularly measured to be 50%-70%, or greater, when the media thickness is 3-6 inches (e.g. Berghage et al 2010, Carter and Rasmussen 2006, Van Woert et al 2005, Moran et al 2005, Van Seters et al 2007, Berghage et al 2009, literature review in Magnuson Klemenic Associates, 2007).  While no green roofs have been monitored for annual stormwater retention in Minnesota, green roofs in Minnesota’s climate (with shorter storms, and generally enough time to allow evapotranspiration to renew much of the soil water holding capacity in between rain events) are expected to retain about 70% of annual runoff. Berghage et al’s results published in 2010 of an extensive green roof with 3” of growing medium in Chicago IL, a climate similar to Minnesota’s climate, found 74% annual retention over a 2 year study period that included 106 precipitation events.

Higher reductions are attainable by maximizing design for stormwater retention and evapotranspiration (e.g. Compton and Whitlow 2006 – see case studies).

Rain that falls on a green roof soaks into the soil and either (1) is evaporated or transpired from the growing media and plants back into the atmosphere, or (2), percolates through the growing medium into the drainage layer under the growing medium and to the roof drains. Surface runoff almost never occurs on a green roof except during massive rainfalls.  The FLL guidelines for saturated hydraulic conductivity of growing medium for multi-course extensive green roofs, for example, is 0.024-2.83 inches per minute. Green roofs are analogous to thin groundwater systems.   Discharge from a green roof is best understood as ‘groundwater baseflow’ from this system.  This is apparent when you consider the time delay between rainfall peaks and discharge peaks on green roofs.  For a green roof area of 5,000 square feet, the delay may be 60 minutes; versus 15 minutes if a surface flow ‘time of concentration’ was calculated using the Mannings formula, or similar.  Green roofs do not have curve numbers, since nothing infiltrates.

Times of concentration in the context of TR-55, do not apply to green roofs.  There should be no surface flow under normal conditions.  Rather, the rate at which water is discharged from the roof depends on the design of the subsurface drainage zone.  The appropriate parameter is transmissivity.

Green roof growing media water storage potential and evapotranspiration (ET) potential are dynamic.

The pattern of water uptake and release from the surface media can be summarized as follows:

1. Initially all moisture is absorbed and no underflow occurs.
2. After about ½ of the maximum water capacity (MWC) is satisfied, the first ‘break though’ of precipitation occurs and underflow begins.
3. The media continues to absorb more water, with increasing efficiency, even as percolation continues.
4. Finally, the capacity of the media to hold water is overwhelmed and the underflow rate will approach rainfall rate for the first time.
5. As the rainfall rate decreases, the moisture content will continue to drop until it attains the MWC (typically 30-40% by volume).
6. After the rainfall has stopped, water will continue to bleed out of the green roof for an extended period. At the same time water is continuously lost to the atmosphere via direct evaporation and plant evapotranspiration. Depending on the type of media, this process may last for days.
7. Eventually, underflow will end. The moisture remaining at this point is associated with field capacity (typically 15-20% by volume). This water will be slowly removed from the media through evapotranspiration of the plants (adapted from Miller 2003).

ET rates also vary over time, depending on climatic conditions, soil moisture, and vegetation vigor, cover, and species. Several studies have shown rapid water loss through ET immediately after a rain event, and much slower ET rates starting 5-10 days after soil was saturated, when plants need to start conserving water to survive (Voyde et al 2010, Rezaei et al 2005).

Preliminary research results indicate that transmissivity of the drainage layer significantly affects how much rain a green roof retains and evapotranspires. Transmissivity of typical geocomposite drain sheets ranges from 0.050 to 0.200 m2/s (ASTM D4716 and ASTM 2396), which is 50 times greater than that of a typical 2 inch granular drainage layer (0.001-0.004 m2/s). Lower transmissivity results in longer residence times for rainfall in the green roof. This translates to more efficient water absorption and longer delay in peak runoff rate. Preliminary research results indicate that green roofs that have a drainage layer with lower transmissivity have significantly higher ET rates.

A model that accounts for these dynamic processes is needed to accurately reflect green roof hydrology. However, studies and field experience have found that maximum media water retention(MMWR) —the quantity of water held in a media at the maximum media density of the media using the ASTM E2399 standard testing procedure provides a very approximate estimate of event green roof runoff retention potential. As noted earlier, the aggregated effect of storage and ET processes in green roofs can result in annual runoff volume reductions of 70 percent, or more. However, the increase in retention storage potential with increasing soil depth is not linear. This is a consequence of the non-uniform moisture distribution in the soil column. Consequently increasing media thickness above 4-6 inches or so does not provide significant increase in retention storage potential in many instances.

**Water Quality Benefits**

**See Task 9 for literature review of studies of phosphorus and TSS reduction in green roofs**

When considering the influence of green roofs on runoff water quality, emphasis should be placed on the total mass of pollutants that may be released.

Rainwater is generally considered non-polluted, but can contain substantial nitrates, as well as traces of other pollutants, such as heavy metals and pesticides (Berndtsson 2010).

Generally, organic material in green roofs can be very effective in binding environmental pollutants such as heavy metals (e.g., zinc, arsenic, cadmium, lead, and copper). Consequently, green roofs are excellent practices where airborne pollution by heavy metals is important. Green roofs can also immobilize complex organic pollutant molecules.

While many research studies have found an increase in nutrients in green roof runoff compared to conventional roofs, several have found green roofs to be beneficial even for nutrient reduction. Studies of nutrients released from green roofs are a good example of the importance of studying total mass of pollutants released rather than percent removal in the effluent, or concentration in the effluent. For example, USEPA (2009) reports higher concentrations for most nutrients and ions in the green roof runoff compared to runoff from the conventional roof, but total mass released was less than from the conventional roof because the green roofs retain more rain than the conventional roof.

Primary sources of nutrients in green roof runoff are atmospheric deposition and leaching from the growing medium and fertilizers.

Aggregates, organic materials and amendments used in formulating green roof media should be tested for nutrients to insure that they will not be a potential long-term sources for contaminants (see Task 6 for more on testing green roof growing media).

For mature green roofs, the mass of major nutrients (e.g., total nitrogen, total phosphorus, potassium, and magnesium) released during the course of one year will be approximately equal to the mass of nutrients contributed by atmospheric deposition and fertilization over the same period. Green roofs that are efficient in detaining and cycling nutrients will require less fertilization and therefore be less of a concern for water quality. Also, the mass of nutrients and pollutants released will decrease as the volume of runoff decreases.

Through professional management of soil fertility, both the concentration and the total mass of nutrients released can be minimized.

To maintain plant vigor, critical nutrients should be restored by periodic fertilization when needed to maintain plant vigor based on soil tests. Fertilization rates should be adjusted to replenish the nutrient ‘reserves’ and stabilize the concentration of soluble nutrients at minimum recommended levels. Fertilize only when needed to maintain plant vigor, and do not include P in fertilizer unless plants need additional P to thrive. See Task 6 for more on soil test and fertilizer.

Rowe (2011) concluded the following in his green roof water quality literature review:

“Overall, it appears that green roofs can have a positive effect on water quality. Based on the data available, green roofs that were a source of pollutants tended to be new, whereas those that were

older with established vegetation were not a problem. The initial nutrient load likely is due to decomposition of organic matter that was incorporated into the original mix. Established vegetation and

substrates can improve the water quality of runoff by absorbing and filtering pollutants. Of course, water quality of the effluent is dependent on several factors such as substrate composition, substrate depth, plant selection, age of the roof, fertilization and maintenance practices, the volume of rainfall, local pollution sources, and the physical and chemical properties of those pollutants. Also, the use of soluble conventional fertilizers should be avoided due to the adverse impact on stormwater runoff. If nutrient loading is a problem green roofs could be coupled with other low impact development practices such as rain gardens and bioswales.”

Until more data is available showing more consistent nutrient reduction from green roofs, green roofs should be used in conjunction with BMPs that are effective for nutrient removal on sites where nutrient reduction is needed.. Alternatively, runoff from the green roof could be harvested and re-used on site. See also the discussion in Task 9 regarding the potential of adding soil amendments to green roofs for phosphorus reduction.