UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 557

Performance Assessment of a Rain Garden for Capturing Suspended Sediments and Phosphorus

By

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Prepared for
LHB Engineers and Architects, Inc.
Duluth, MN

August, 2011
Minneapolis, Minnesota

Acknowledgements

LHB Engineers and Architects, Inc. provided funding for this project. The involvement of the project manager, Dan Shaw, is greatly appreciated. Several individuals assisted in completing this project through field and laboratory work including Ben Erickson, Elliot Spronk, and Lanre Adekola. Their assistance is also appreciated.

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1. Introduction

With the implementation of the United States Environmental Protection Agency's (USEPA) national pollution discharge elimination systems (NPDES) Phase I and II programs, much interest has developed in the area of water quality treatment of stormwater runoff. Of primary water quality concern are sediment and nutrients such as phosphorus (P). Dirt, sand, and other solid particles are commonly quantified by measuring the total suspended solids (TSS) of a water sample. TSS can severely and negatively impact an aquatic environment. The solids increase turbidity, inhibit plant growth and diversity, affect river biota, and reduce the number of aquatic species (Shammaa et al., 2002). Excess nutrients such as phosphorus can initiate large algae blooms that generate negative aesthetic and eutrophic conditions in receiving lakes and rivers. In inland water bodies, phosphorus is typically the limiting nutrient (Schindler, 1977) and can be contributed to storm water from various sources such as fertilizers, leaves, grass clippings, etc. (U.S. EPA., 1999). Total suspended solids and phosphorus are primary concerns of most storm-water management plans, and little is known about the cost effectiveness of available storm-water treatment options.

While some have studied the cost-effectiveness of available stormwater treatment practices (e.g., Weiss et al., 2007), many municipal and state agencies are now required to meet certain pollutant removal criteria based on the USEPA requirements. To meet these requirements, development or redevelopment of land must include stormwater treatment practices to achieve these pollutant removal criteria. Some stormwater treatment practices were installed at 6400 West 105th street in Bloomington, MN to protect downstream water resources by reducing stormwater runoff volume and improving runoff water quality. This project measured the performance of one such practice, a rain garden, to determine the reduction of stormwater runoff volume and the pollutant capture effectiveness, specifically for dissolved phosphorus and suspended sediment.

The rain garden is one of two rain garden basins that temporarily hold and infiltrate excess stormwater runoff into the soils during a rainfall event. The rain gardens receive stormwater runoff from the roof of an adjacent building, through rooftop downspouts that discharge directly into the rain garden. As runoff begins to fill the rain gardens, it infiltrates into the rain garden soils and subsequently into the subsurface soils. If the rain gardens receive too much stormwater, some stormwater passes through a 6-inch perforated under-drain that was installed approximately 18 inches below the surface. The two rain garden basins are separated by a berm perpendicular to the length of the rain garden. A cleanout is located approximately in the center of the smaller upstream rain garden and extends approximately 12 inches above the surface of the rain garden. A picture of the rain garden tested as part of this project is shown in Figure 1.

Figure 1: Site photo of rain garden.

Testing was performed on the smaller upstream rain garden because it could be filled in a relatively short period of time with a standard fire hydrant, which was located nearby. This rain garden is approximately 90 feet long (east-west) and 30 feet wide (north-south) and receives approximately 14,000 gallons when a 1-year, 24-hour rainfall event (2.4 inches) occurs over the contributing watershed (rooftop). The cross-sectional detail used for construction of this rain garden is shown in Figure 2.

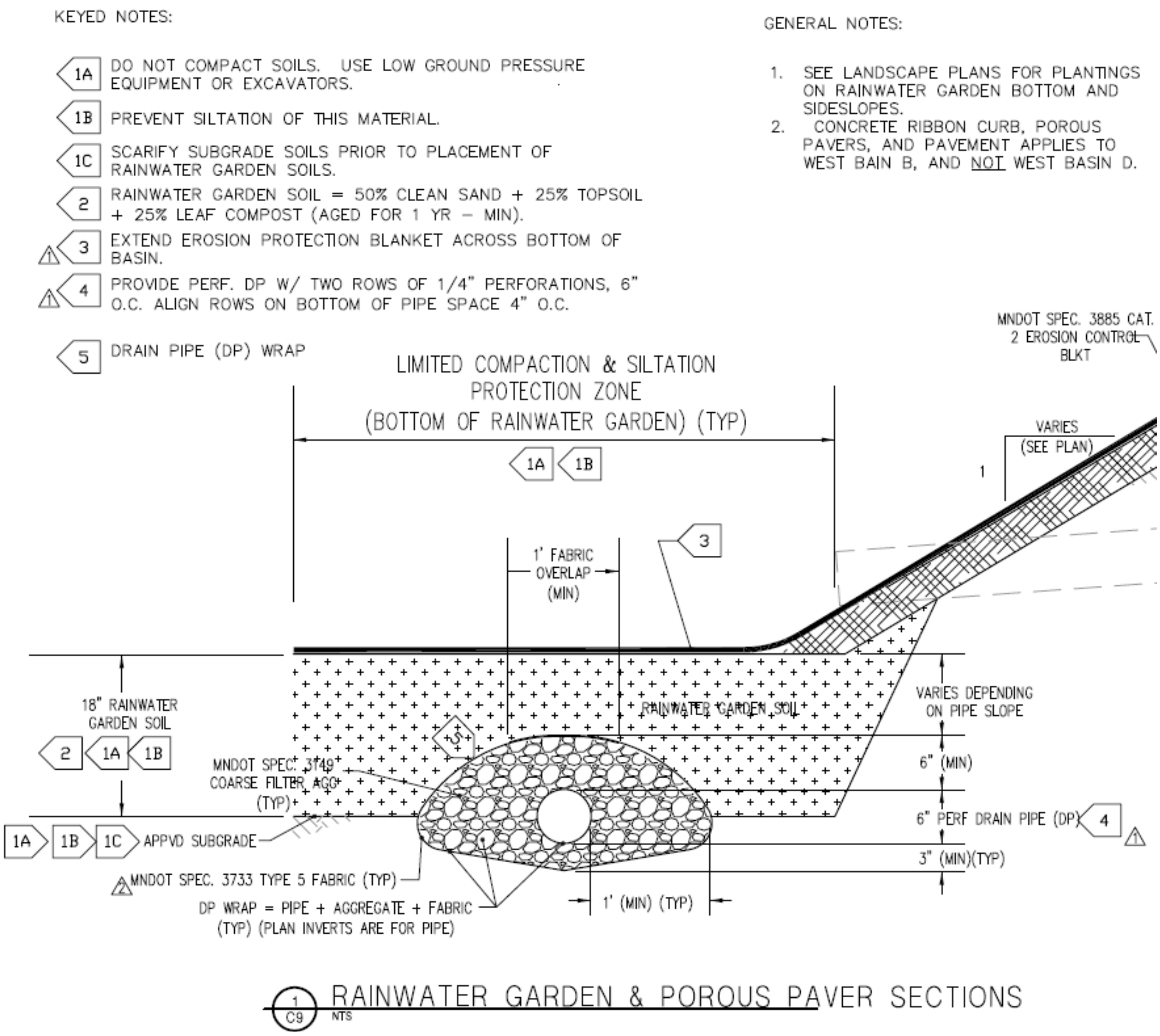

Figure 2: Rain garden construction detail.

2. Methods

The performance of the rain garden was tested using water drawn from a nearby fire hydrant to simulate stormwater. A flow meter and length of hose were attached to the fire hydrant and the water was turned on in order to fill the rain garden. During testing, a vertical extension was attached to the cleanout to prevent water from draining through the cleanout and thus bypassing the rain garden. The influent flow rate for each test was set to approximately 300 gallons per minute (gpm) and the actual flow rate was recorded approximately every five minutes, as shown in Figure 3. Approximately 5,500 gallons of water were added to the rain garden during the test on November 11, 2010 and approximately 14,000 gallons were added during the tests on June 22, 29, and 30, 2011.

Figure 3: Adding synthetic runoff to the rain garden using a fire hydrant, fire hose, and flow meter.

Infiltration was measured by securing a measuring rod vertically at the lowest point of the rain garden, as shown in Figure 4. Water level was measured at one-minute intervals while the rain garden was filled with water and at fifteen-minute intervals while the water in the rain garden infiltrated into the soils.

Figure 4: Water level measurements within the rain garden.

The effluent flow rate of stormwater was intended to be measured at the outlet of the under-drain system, as it discharged into the overflow manhole at the west end of the rain gardens. Outflow was not observed, however, during any of the synthetic runoff tests nor during any of the large natural stormwater events observed at the site.

Samples were collected in two locations: from the discharge of the fire hydrant (inflow) and at the outlet of the under-drain system (outflow). Samples were collected using acid-washed glass sample bottles. Samples were collected, stored, and transported back to St. Anthony Falls Laboratory to be analyzed for dissolved phosphorus concentration according to standard methods section 4500-P E (Ascorbic Acid) with a minimum detection limit of 0.010 mg P/L (American Public Health Association, 1998).

3. Results and Discussion

The performance of the rain garden was measured with four individual synthetic runoff tests: November 11, 2010; June 22, 29, and 30, 2011. Each test was conducted under slightly different conditions to determine the variation in possible infiltration rates for this rain garden. The climatic conditions for each of these tests are shown in Table 1.

Table 1: Climatic conditions for synthetic runoff testing (Source: www.noaa.gov).

Test Date	11/11/2010	6/22/2011	6/29/2011	6/30/2011
Minimum daily temperature [°F]	37	53	62	72
Average daily temperature [°F]	45	62	74	84
Maximum daily temperature [°F]	52	70	86	95
Previous day rainfall [inches]	0.17	1.20	0	0
Previous 5-day rainfall [inches]	0.17	2.28	0	0
Previous day synthetic runoff [inches]	0	0	0	2.41
Current day synthetic runoff [inches]	0.95	2.52	2.41	2.41
Initial soil moisture [%]	N/A	10.4%	N/A	N/A

As listed in Table 1, the climatic conditions of the four tests are significantly different. In general, the rain garden was tested under cold, dry conditions (November 11, 2010); warm, wet conditions (June 22, 2011); hot, dry conditions (June 29, 2011); and hot, wet conditions (6/30/2011). As the temperature decreases, the viscosity of the water increases which results in a reduced infiltration rate (Daily and Harleman, 1966). Conversely, as the initial soil moisture decreases (becomes more dry), the initial infiltration rate increases (Mays, 2005). The tests that were conducted included cold, warm, and hot days as well as dry and wet soil conditions and therefore the measured saturated hydraulic conductivity represents most conditions for which infiltration occurs. The water level data collected during the four field tests are shown in Figure 5.

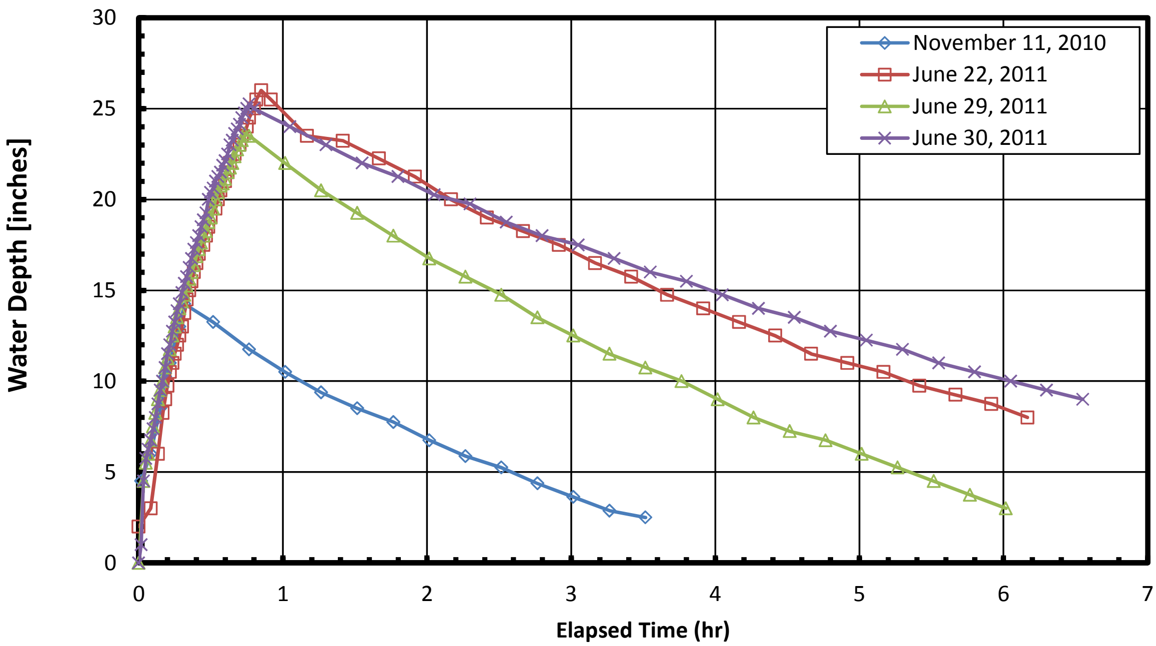

Figure 5: Water level data from four field tests conducted on the rain garden.

The synthetic hydrographs generated during these tests are composed of two parts; 1) a near-constant increase in water level (i.e., rising limb) lasting between 18 and 51 minutes for the four tests, and 2) a near-constant decrease in water level (i.e., falling limb) lasting between 3.22 and 5.78 hours, as shown in Figure 5. A summary of the field testing results is provided in Table 2. Nearly three times as much water was added during the tests in June 2011 as compared to the test in November 2010, corresponding to approximately three times longer fill times. The water depth, however, is approximately only twice as large for the June 2011 tests compared to November 2010 due to the bathymetry of the rain garden (surface area increases with depth).

Table 2: Testing results summary.

Test Date	11/11/2010	6/22/2011	6/29/2011	6/30/2011
Fill time [minutes]	18	51	44	46
Fill volume [gallons]	5,500	14,600	14,000	14,000
Maximum water depth [inches]	14.25	26	23.63	25.25
Drain time [hours]	3.22	5.32	5.28	5.78
Final water depth [inches]	2.5	8	3	9
Average water level rate of descent [inches/hour]	3.64	3.33	3.86	2.77

As listed in Table 1, the volume of synthetic runoff added to the rain garden during the November 2010 test was equivalent to the volume of runoff generated from a 0.95-inch rainfall event. It is important to note that no outflow occurred during the test on November 11, 2010, and thus all of the influent synthetic stormwater was infiltrated into the surrounding soils. Approximately 92.5% of the rainfall events in a normal year are less than approximately 1-inch

(Gulliver et al., 2010; Minnesota Stormwater Steering Committee, 2005). For most storm events, the rain garden is expected to perform similar to the synthetic runoff test conducted on November 11, 2010.

The total volume reduction, however, includes both the total volume of storms completely captured by the practice and the portion of larger storms that is captured before overflow (Gulliver et al., 2010). No outflow occurred during the test in November 2010, which was equivalent to the volume of runoff generated from a 0.95-inch rainfall event. Therefore, the total volume reduction is the sum of the volume of runoff from all storm events less than or equal to 0.95 inches in depth plus the first 0.95 inches of depth from all larger storm events. Approximately 94.5% of the total precipitation depth in a normal year is less than 0.95 inches.

The volume of synthetic runoff added to the rain garden during the June 2011 tests was equivalent to the volume of runoff generated from a 2.4 – 2.5-inch rainfall event. It is important to note that no outflow occurred during the tests in June 2011 and thus all of the influent synthetic stormwater was infiltrated into the surrounding soils. For large storm events (up to 2.5 inches), the rain garden is expected to perform similar to the synthetic runoff tests conducted in June, 2011. Approximately 99.3% of rainfall events, and 98.3% of the total precipitation depth, in a normal year are less than 2.5 inches (Gulliver et al., 2010; Minnesota Stormwater Steering Committee, 2005). This rain garden is expected to capture and infiltrate at least 99% of the runoff events and 98% of the total rainfall depth during a normal rainfall year.

Because no outflow from the rain garden was observed during these tests, no effluent samples were collected. Without effluent samples, it is impossible to calculate water quality performance. It is possible to estimate that 100% of the pollutants in storms that do not produce outflow are captured in the rain garden or infiltrated into the surrounding soils. Pollutant concentration in natural stormwater runoff varies substantially and is not necessarily related to rainfall or runoff characteristics. If pollutant concentration is assumed to be constant with respect to rainfall (or runoff), then the pollutant reduction can be assumed to be equal to the volume reduction. In other words, 5% of the total rainfall depth will produce exactly 5% of the total pollutant load. When the pollutant concentration is positively related to rainfall (or runoff), then more of the total pollutant load (load = concentration x volume) is delivered downstream with larger storm events. This can result in, for example, 5% of the total pollutant load being delivered downstream during the largest 2% of the rainfall events. Although runoff water quality was not measured during these tests, it can be assumed that most pollutants (>95%) from most storm events will be captured in the rain garden because 99% of the rainfall events (98% of the total rainfall volume) is captured within the rain garden without outflow or overflow.

An accurate estimate of the infiltration rate is given by the Green-Ampt model, given in Equation 1. Of the parameters required to solve the Green-Ampt equation, the initial depth of water (h_0), depth of water at time t ($h(t)$), and elapsed time of infiltration (t) were measured during the experiments. The remaining Green-Ampt equation parameters, change in soil moisture ($\Delta\theta$), soil suction head (Ψ_s), and initial depth of infiltrated water (F_0) were assumed or estimated as follows.

Equation 1: Green-Ampt equation for infiltration with positive, non-zero head, assuming water is not instantaneously added.

$$k = \frac{\dfrac{h_0 - h(t)}{1-\Delta\theta} + \left(\dfrac{-\left(h_0 + \Psi_s\right)\Delta\theta}{1-\Delta\theta}\right)\left[\ln\left(1 + \dfrac{\left(h_0 - h(t)\right)\left(1-\Delta\theta\right)}{\left(h_0 + \Psi_s\right)\Delta\theta + F_0}\right)\right]}{t}$$

Where: k = saturated hydraulic conductivity [in/hr]
h_0 = initial depth of water [inches]
$h(t)$ = depth of water at time t [inches]
$\Delta\theta$ = change in soil moisture [-]
Ψ_s = soil suction head [inches]
ln = mathematical operator for natural logarithm
F_0 = initial depth of infiltrated water [inches]
t = elapsed time of infiltration [hours]

The change in soil moisture is a difference between the final and initial soil moisture ($\Delta\theta = \theta_{final} - \theta_{initial}$). The initial soil moisture was determined from five soil samples collected at the site before the synthetic runoff test on June 22, 2011. The average soil moisture of these five samples was 10.38%, and this value was assumed to be representative of the initial soil moisture for all the tests. The final soil moisture is often assumed to be 100% of the pore volume and average values for pore volume for sandy soils commonly used in rain gardens is 43.7%. Therefore, the change in soil moisture is assumed to be 33.3% for all tests. It has been found that the change in moisture content has a less than a 20% effect on saturated hydraulic conductivity (Regalado et al., 2005). This can be considered minor relative to the orders of magnitude difference that occurs over space in one rain garden (Asleson et al., 2009).

The soil suction head (Ψ_s) is the amount of negative pressure the soil imparts on water as it infiltrates into the soil. An average value for soil suction head is 4.95 cm (1.95 inches) (Mays, 2005), which was assumed for all tests.

The initial depth of infiltrated water (F_0) was estimated using a form of the Green-Ampt equation that results from assuming the water used the fill the basin is instantaneously added (Equation 2). For the amount of time it takes to fill the basin (the rising limb), this assumption is a reasonable approximation. The mid-depth of water (h_m) is assumed to be approximately represented by the average water depth during the rising limb, which can be simply estimated as half of the max depth (i.e., $h_m = ½ h_0$). Because both the initial depth of infiltrated water (F_0) and the saturated hydraulic conductivity (k) appear in equations 1 and 2, the initial depth of infiltrated water (F_0) can only be determined by solving equations 1 and 2 simultaneously to solve for the depth of infiltrated water (F_0).

Equation 2: Green-Ampt equation for infiltration with positive, non-zero head, assuming water is instantaneously added.

$$k = \frac{F_0 - \Delta\theta(\Psi_s + h_m)\ln\left(1 + \frac{F_0}{\Delta\theta(\Psi_s + h_m)}\right)}{t}$$

Where: k = saturated hydraulic conductivity [in/hr]
F_0 = initial depth of infiltrated water [inches]
$\Delta\theta$ = change in soil moisture [-]
Ψ_s = soil suction head [inches]
h_m = mid-depth of water [inches]
ln = mathematical operator for natural logarithm
t = elapsed time of infiltration [hours]

The input values used in Equation 1 and the resulting saturated hydraulic conductivity (k) are summarized in Table 3 for all the tests. The variability in saturated hydraulic conductivity during each of the tests is illustrated in Figure 6. Because these tests represent a range in climatic conditions, the saturated hydraulic conductivity for most storm events is expected to be between 3 and 6 inches per hour.

Table 3: Green-Ampt equation parameters.

Test Date	11/11/2010	6/22/2011	6/29/2011	6/30/2011
Initial Moisture Content (θ_i) [-]	0.104	0.104	0.104	0.104
Change in Moisture Content ($\Delta\theta$) [-]	0.333	0.333	0.333	0.333
Soil Suction Head (ψ_s) [inches]	1.95	1.95	1.95	1.95
Mid-depth (h_m) [inches]	7.1	13.0	11.8	12.6
Initial Infiltration (F_0) [inches]	3.97	9.06	8.53	7.16
Green-Ampt saturated hydraulic conductivity (k) [inches/hour]	4.53	4.58	5.06	3.60

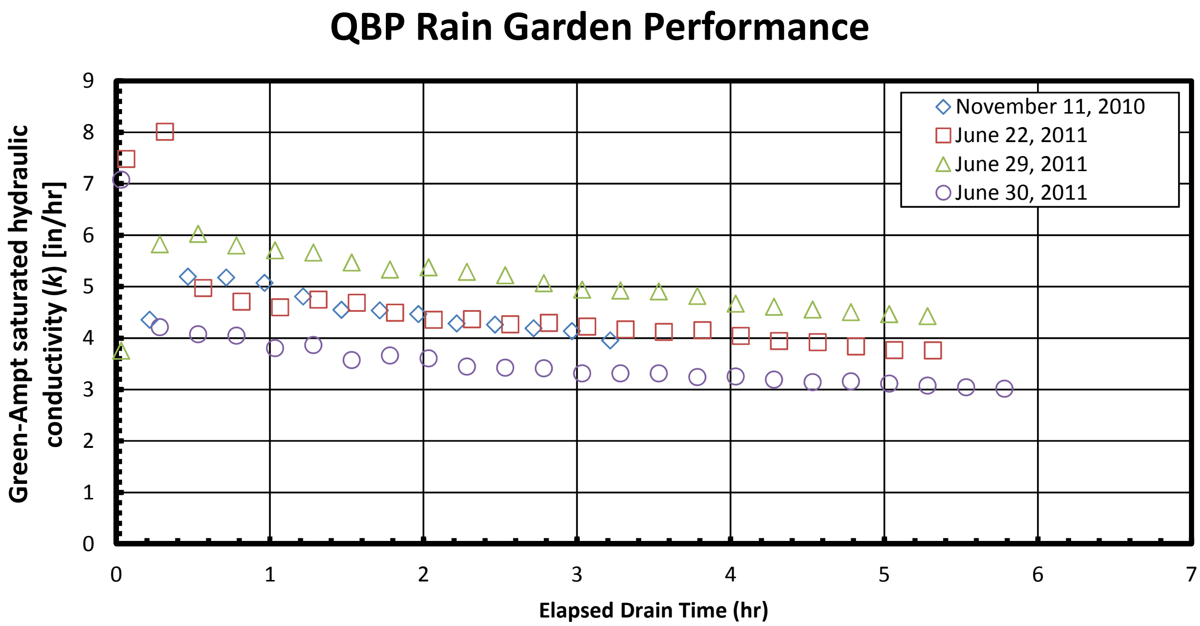

Figure 6: Variation in saturated hydraulic conductivity during four tests.

From the test data, it is possible to estimate the average rate at which the water level descends as synthetic stormwater infiltrates into the rain garden soils (see Table 2, Figure 7), which varied from 2.77 to 3.86 inches per hour. As shown in Figure 7, the average water level rate of descent (i.e., linear curve-fit) does not capture the curvature evident in the water level measurements, but does provide an approximate estimate of the rate at which the water level will decrease over time.

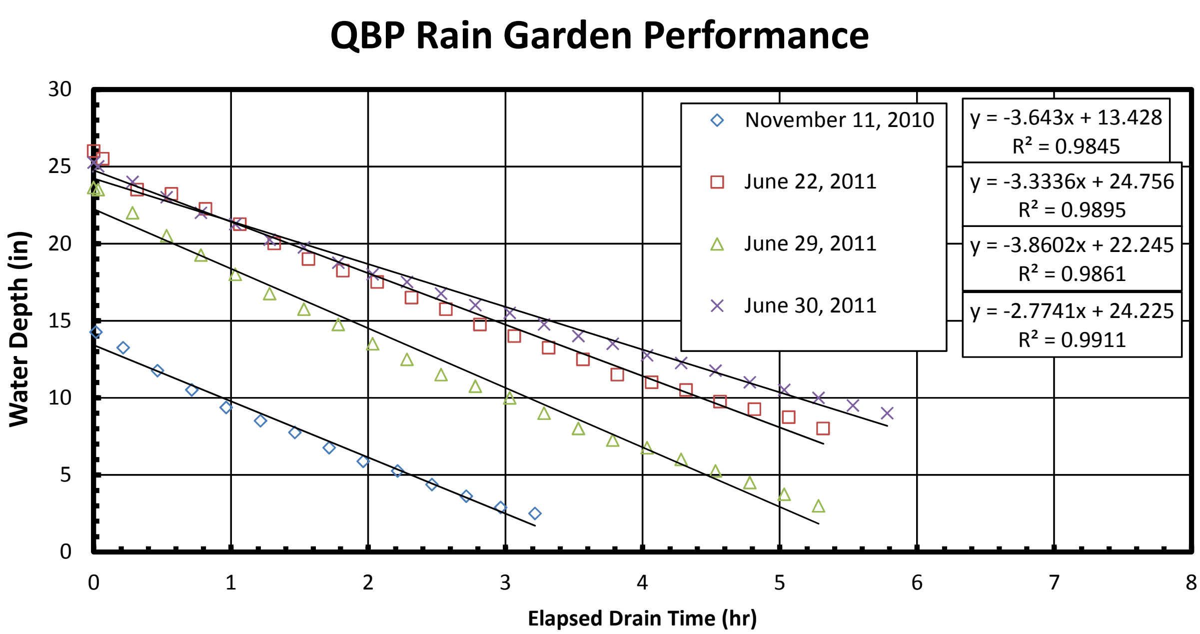

Figure 7: Synthetic hydrograph falling limb water level data and estimate of water level rate of descent.

4. Conclusions

This project measured the performance of a rain garden installed at 6400 West 105th street in Bloomington, MN for reduction of stormwater runoff volume, dissolved phosphorus, and suspended sediment. Several synthetic runoff tests were conducted under various climatic conditions ranging from cold to hot and dry to wet. This range is expected to represent most storm events that will occur at this site. The synthetic runoff events also represented the runoff volume from rainfall events up to 2.5 inches in depth, which accounts for 99% of rainfall events and 98% of the total precipitation depth in a normal year. No outflow was observed from 3 different synthetic runoff events representing a 2.5-inch rainfall, and therefore the rain garden is expected to achieve 98% total volume reduction. Although no outflow was observed and subsequently no effluent samples were collected, the rain garden is expected to capture or infiltrate at least 95% of the influent dissolved phosphorus and total suspended solids because 98% of the inflow volume is infiltrated without outflow or overflow.

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6. Appendix A – Derivation of the Green-Ampt Equation

To determine the overall average saturated hydraulic conductivity of the practice, the Green-Ampt equation (Equation 3) can be rewritten as Equation 4.

Equation 3: Green-Ampt equation.

$$f = k\left[\frac{(\theta_i - \theta_f)(\Psi_s + z_w)}{F} + 1\right]$$

Where: f = infiltration rate into the soil [in/hr]
k = saturated hydraulic conductivity [in/hr]
θ_i = initial volumetric moisture content of the soil[-]
θ_f = final volumetric moisture content of the soil[-]
Ψ_s = soil suction at the wetting front (a positive value) [inches]
z_w = head of water on the soil (i.e. water depth in the practice) [inches]
F = cumulative depth of water infiltrated [inches]

Equation 4: Differential form of the Green-Ampt equation.

$$\frac{dF}{dt} = k\left[\frac{(H + \Psi_s)\Delta\theta + F_d(1 - \Delta\theta) + F_0}{F_0 + F_d}\right]$$

Where: F = cumulative depth of infiltrated water [inches]
t = elapsed time of infiltration [hours]
k = saturated hydraulic conductivity [in/hr]
H = depth of water above the soil surface at time = 0 [inches]
Ψ_s = soil suction head [inches]
$\Delta\theta$ = change in soil moisture, $\Delta\theta = \theta_i - \theta_f$ [-]
F_d = depth of infiltrated water [inches]
F_0 = initial depth of infiltrated water [inches]

Note that Equation 4 was developed with the assumption that the sum of F_0 and F_d, at any given time, is the total depth of infiltrated water and the depth of water (h) is equal to depth of water above the soil surface at time = 0 minus the depth of infiltrated water ($h = H - F_d$).

Separating variables in Equation 4 and integrating yields an implicit solution for the depth of infiltrated water (F_d) as a function of time, given in Equation 5.

Equation 5: Integrated form of the Green-Ampt equation.

$$k = \frac{\dfrac{F_d}{(1-\Delta\theta)} + \left[-\dfrac{(H + \Psi_s)\Delta\theta}{(1-\Delta\theta)}\right]\left[\ln\left(1 + \dfrac{F_d(1-\Delta\theta)}{(H+\Psi_s)\Delta\theta + F_0}\right)\right]}{t}$$

The depth of infiltrated water (F_d) can be redefining as the difference between the initial depth of water (h_0) and the depth of water at time t ($h(t)$), yielding $F_d = h_0 - h(t)$. For consistency, the depth of water above the soil surface at time = 0 (H) can also be redefined as initial depth of water (h_0), yielding $H = h_0$. Substituting these into Equation 5 yields the Equation 1 described in the text and used to determine the saturated hydraulic conductivity.