# ABSTRACT

Title of Thesis: BIORETENTION/CISTERN/IRRIGATION TO ELIMINATE STORMWATER RUNOFF AT THE UNIVERSITY OF MARYLAND

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Water quality of parking lot (~1,858 $m^2$) stormwater runoff and its treated effluent flow were analyzed for total phosphorus (TP), total nitrogen (TN), total suspended solids (TSS), electrical conductivity (EC), copper, lead and zinc. The novel system under investigation, located at the University of Maryland, College Park, Maryland, includes a standard bioretention facility, underdrained to a cistern to store treated stormwater, and pumped to a vegetable garden for irrigation. The site abstraction, the average bioretention abstraction, and bowl volumes were estimated to be 8500, 4378, and 895 L, respectively; this indicates that rain events of more than 0.45 cm are necessary to produce runoff and more than 0.75 cm will produce system overflow. The cistern water quality indicates good-to-excellent treatment by the system. Compared to local tap water, cistern water has lower concentrations of TP, TN, EC (non-winter), copper, and zinc, indicating a good water source for irrigation.

# BIORETENTION/CISTERN/IRRIGATION TO ELIMINATE STORMWATER RUNOFF AT THE UNIVERSITY OF MARYLAND

by

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# CHAPTER 1. INTRODUCTION

As the world population keeps increasing, our existing infrastructure is becoming highly impervious and will expand more in the future. These impervious areas, such as rooftops, paved roadways, walkways, and parking lots, greatly contribute to the change of the hydrologic characteristics of rainfall/runoff and water quality of stormwater runoff. As stormwater runoff is magnified and accelerated from larger impervious areas, it tends to increase downstream soil erosion, carry more pollutants, and change downstream water body temperature (hotter in the summer). The result of heavy urbanization also leads to bed and bank erosion and channel enlargement in streams, which are directly caused by larger runoff volumes and shorter times of concentration (lag time between rainfall and runoff) (Konrad et al. 2005). The increased runoff reaches natural banks, erodes them as a long-term effect, and pollutes the aquatic environment.

Urban stormwater runoff has become one of the leading sources of water quality impairment in lakes, ponds, reservoirs, rivers and estuaries (USEPA 2000). High nutrient inputs, suspended solids, and heavy metal concentrations are some of the greatest water quality problems. Best Management Practices (BMPs) also known as Stormwater Control Measures (SCMs), such as bioretention, detention ponds, grass swales and more, are being used more intensively in urban areas to provide adequate flow management and treatments to improve runoff quality (Hsieh and Davis 2005).

In urban runoff, the most basic pollutant is suspended particles. These suspended particles are eroded particulates from soils, such as clays, silts, and fine sands; wear particulates from vehicles (tires, brakes, and rotors); and from construction and buildings (Davis et al. 2003, 2006). Suspended particles or total suspended solids (TSS) can negatively impact aquatic ecosystems (Davis and McCuen 2005). These particles reduce natural water quality through various mechanisms. TSS commonly carry a number of toxic pollutants (e.g. phosphorus compounds and heavy metals) that can endanger downstream aquatic life. Various SCMs can provide sufficient removals of TSS, such as sand filters, stormwater filters, grass swales, bioretentions/rain gardens, infiltration trenches, and vegetative buffering zones. Past reports have shown that bioretention/rain garden provides a good-to-excellent removal of TSS and heavy metals compared to other SCMs (Davis et al. 2003, 2006; Davis 2007) because of its filtration characteristics (e.g. soil type).

Bioretention is a stormwater management facility that contains various layers of mulch/soil/sand/gravel media. It allows stormwater runoff to be collected and ponded in the bowl (the storage volume above the bioretention surface) and to be filtered through layers of media. These two main functions of bioretention provide mitigation of stormwater runoff volume and speed, and the removal of TSS, certain nutrients, and heavy metals. These processes are performed through evapotranspiration (ET), infiltration (removal of TSS), biological transformations (nitrification and denitrification processes), and adsorption processes (phosphorus and heavy metals).

The increase of urbanization typically decreases water volume recharging into the ground because natural land is converted to impervious area; hence, it reduces the pervious surface area for filtration and the availability of groundwater supplies. Facing long drought in major cities of Australia (e.g., Brisbane, Melbourne, and Sydney), research focused on harvesting stormwater (from rooftops), was conducted to provide additional water sources (Rose and Peters 2001; Fletcher et al. 2008; Llopart-Mascaró et al. 2015). As reported, the collected stormwater runoff was treated at different levels depending on the use (e.g., irrigation, carwash, and toilet flush). To increase water-recharge rate into the ground, technologies like biofiltration and porous pavement are implemented into post development areas (Davis et al. 2009; Houdeshel et al. 2015; Mangangka et al. 2015). Having these types of SCMs within urban areas will help to capture more stormwater runoff (less stormwater released to downstream water bodies), provide treatments to pollutants, and increase water recharge into groundwater for future use.

Knowing negative effects of stormwater runoff and its carried pollutants to downstream water ecosystem (e.g., water impairment and flooding), it is better to maximize the runoff volume captured by a SCM, treat the runoff, and use it for irrigation instead of releasing it to downstream areas. In order to do so, a combination of a bioretention, a cistern chamber, and a local vegetable garden is constructed and connected to collect and treat stormwater runoff from a parking lot at The University of Maryland, College Park, Maryland. This work has two specific objectives (1) to investigate the feasibility of the system to minimize the runoff overflow and (2) to examine the safety of treated water for the irrigation of a vegetable garden. The water balance of the drainage area and the constructed system is estimated from rainfall volume, runoff volume, maximum bioretention abstraction volume, and water gained in the cistern chamber. The influent and cistern water samples are analyzed for TSS, total phosphorus (TP), total nitrogen (TN), copper, lead, and zinc. The results will show the removal efficiency of the system. The water quality of cistern water sample will be compared with local tap water and with data from Potomac Water Filtration Plant, Potomac, Maryland. Also, the salinity and pH of the stormwater runoff will be reported to ensure that the effluent water is appropriate for irrigation purpose.

# CHAPTER 2. METHODOLOGY

## 2.1 Site Description

The drainage area (yellow box) is located near the Eppley Recreation Center and the School of Public Health, The University of Maryland, College Park, Maryland. It is an impervious parking lot of 1,858 $m^2$ (20,000 $ft^2$) (Figure 2.1.1). Based on the characteristics of the drainage area, it may provide minimal site abstraction volume (SAV), the amount of water needed to saturate the drainage area before runoff may occur. The stormwater runoff from this drainage area enters a stormwater control measure (SCM) for treatment of pollutants. Additionally, some runoff from adjacent areas (from the left side of the yellow box in Figure 2.1.1), mostly grass, also enters the system.

A standard bioretention system (red box), as a SCM, was constructed between the Eppley Recreation Center and the School of Public Health (Figure 2.1.1). The bioretention facility was designed into three cells (10.81−5.76−5.87 $m^2$) on a steep narrow landscape. The designed drawing plan of the bioretention facility indicates that each cell has 0.61 m (2 ft) of soil media (15% double shredded hardwood mulch, 50% washed sharp sand (ASTMC-33), 30% topsoil, and 5% volume peatmoss by volume) to provide infiltration and treatment of inflow runoff. The soil media must be sampled and tested to identify the exact soil type to support hydrologic calculations. Temporarily, it is assumed to be sandy loam. The bioretention also includes some rip-rap portions between cells to reduce water runoff velocity (Figure 2.1.2 c). These rip-rap sections protect the bioretention cells from soil erosion and clogging by eroded soils. At the 3$^{rd}$ cell, there is an overflow cage to allow stormwater runoff enter the university stormwater system (Figure 2.1.2 and 2.1.4). The overflow cage also is protected by a fence to avoid clogging

(Figure 2.1.5) Finally, an underdrained pipe (6” perforated PVC, ASTM-D3034 SDR-35) was installed at the bottom of the bioretention to collect and convey treated water to a cistern chamber.

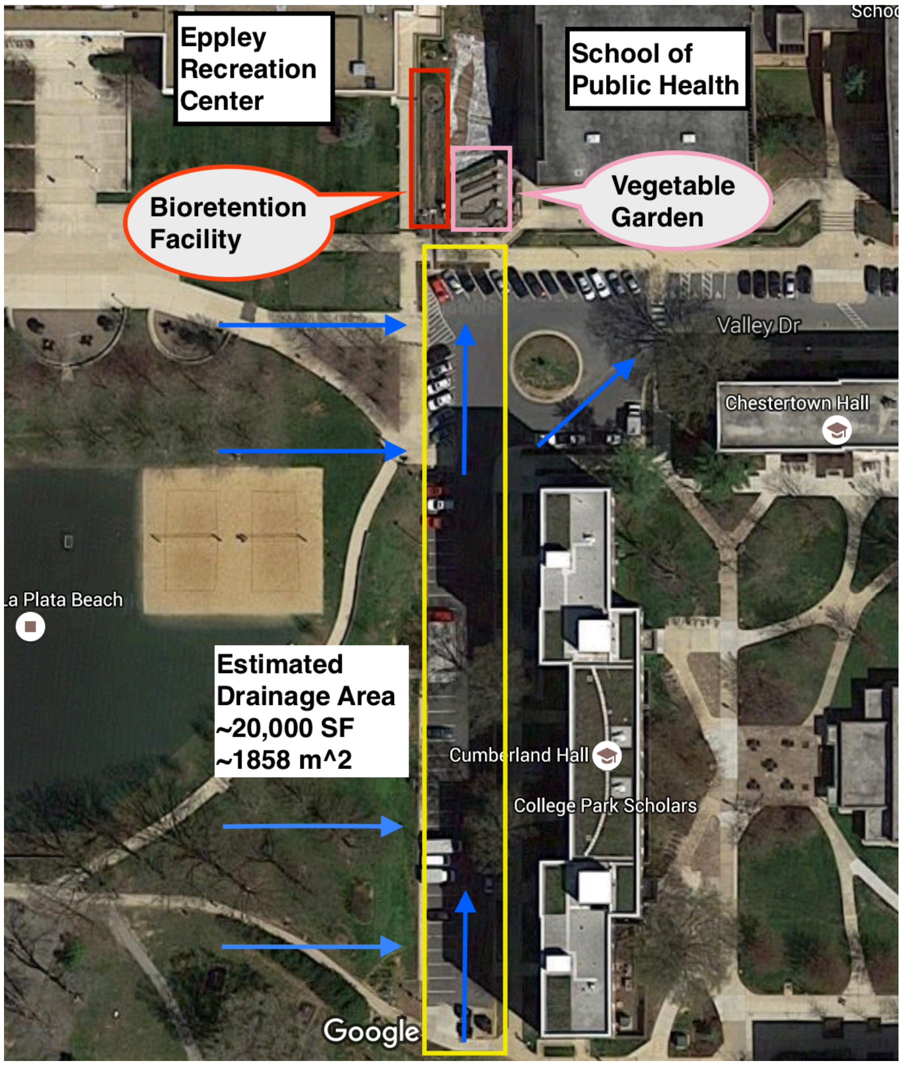



**Figure 2.1.1**. A map showing the site and the installed facilities near the Eppley Recreation Center and The School of Public Health at the University of Maryland. The yellow rectangular box is the estimated drainage area. The water runoff (blue arrows) from this area enters the bioretention system (red box) for treatment (Lat 38.993179, Long -76.944310). The effluent from this facility is stored in a cistern and directed to the local vegetable garden (pink box) (Lat 38.993166, Long -76.944220) for irrigation.

The cistern, a cylindrical chamber (dia. 1.5 m : L 5.4 m) with the storage up to 9,100 L, is installed horizontally at the end of the bioretention system connected by an underdrained pipe (Figure 2.1.3). At the opening of the cistern, there is a riser (dia. 0.61 m: H 0.91 m). Cistern water can either be pumped back to the entrance of the bioretention during winter season for further treatment or be pumped up to the adjacent vegetable garden for irrigation purpose (Figure 2.2.1). A solar panel was installed near the cistern to provide energy for pumping treated water out of the cistern (Figure 2.1.4).

The Public Health garden is constructed next to the bioretention cistern (Figure 2.1.5). It has 7 identical water barrels that can hold up to 1,300 L in total to irrigate vegetables. There are many types of vegetables planted since 2014, such as, tomato, squash, hot pepper, spinach, and berries.

a) Pre-construction (2011)

b) Construction phase (2012-2013)

c) Post construction (2013)

| | |
|---|---|
|  d) Planting phase (2013) | |

**Figure 2.1.2**. The construction of bioretention/cistern site.

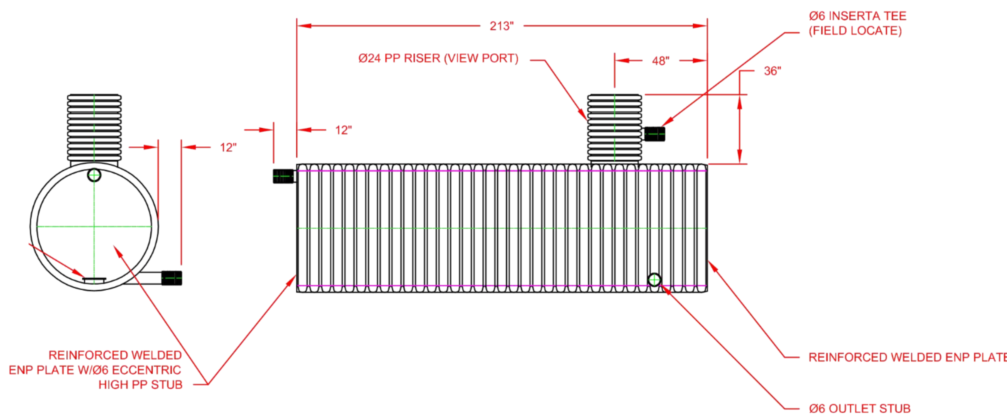



**Figure 2.1.3**. The design parameters of the cylindrical cistern/riser.

Figure 2.1.4 shows a large storm event that occurred in 2014. When the bioretention cells are completely saturated, generally caused by high rainfall intensity, the stormwater runoff flows over the surface of these cells. When the bowl volume of cell 3 is full, a portion of the untreated runoff builds up and flows into the overflow inlet, connected directly to the city stormwater system. Hence, during storms that have large rainfall intensity, this bioretention facility will not fully capture the runoff. Figure 2.1.4 shows that the stormwater runoff overflowed the 3rd cell and caused flooding because the berm was not constructed appropriately. The level of the overflow inlet is partially higher than the berm. In 2015, the berm at 3rd cell was reconstructed to be higher than the overflow inlet (Figure 2.1.5).

Regular monitoring (April 2014) – B1

**Figure 2.1.4**. Site responses from a large rain event in 2014, before the construction of higher berm.

**Figure 2.1.5**. Current condition of the Public Health Garden set up; bioretention cells with growing plants, an enhanced berm at cell 3, protected overflow inlet, and a functioning solar pump.

Figure 2.1.5 shows the current condition of the whole system. The vegetable garden is full of vegetable species and is using the treated water from the cistern for irrigation. Plant species within the bioretention cells also were reconstructed to slow flow. Moreover, another layer of mulch was applied over the surface as a new source of carbon and organic matter. The overflow inlet was protected and the berm was enhanced to control the overflow volume properly. Finally, a solar panel and a pump were completely installed to recirculate treated water to the bioretention cells (winter season) and to the vegetable garden (seasons other than winter).

**2.2 Monitoring and Sampling Methodology**

At the entrance of the bioretention cell (Figure 2.2.1), an auto-sampler (ISCO 6712) was installed to collect water samples and to measure the water level in a 0.41m W x 0.91m L cutthroat flume (Tracom). The runoff level was logged into the system at 2-min intervals by a bubbler sensor attached in the flume. Based on the charateristics of the flume, the flow rate is estimated (Eq. 2.2.1) from the water level inside the flume (Skogerboe et al. 1972). This equation is recommended to use for flow of more than 3.05 cm depth. With the flow of less than 3.05 cm, the result from this equation will be less reliable. Additionally, the runoff volume, *V*, was calculated based on a simple numerical integration of flow measurements over time.

$$Q(t)\ (\text{L/s}) = 1522\ H_m^{1.84} \qquad \text{(Eq. 2.2.1)}$$

$$V = \sum Q(t)\Delta t \qquad \text{(Eq. 2.2.2)}$$

where: $Q(t)$ (L/s) is the runoff flow rate;

$\Delta t$ (s) is the time interval between each measurement (typically 120 seconds).

$H_m$ (m): water levels in the flume.

The influent samples are collected as volume-weighted composite samples from rain events. The auto-sampler is programed to take the first water sample (100 mL) when the water runoff reaches 3.05 cm inside the flume, and 100 mL after every 1000 liters (Sample 1 in Figure 2.2.1). To collect sample 1, two cleaned plastic bottles (200 mL each) are used to store and preserve water for water quality testing. An ISCO 670 rain gauge was installed at the site to measure the rainfall (cm of water) of the drainage area. Hence, the rainfall volume is calculated from the product of rainfall and the drainage area estimates the theoretical flowrate.

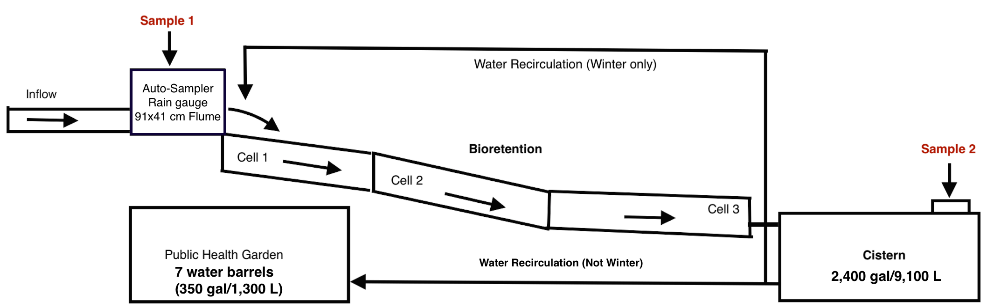



**Figure 2.2.1**: University of Maryland bioretention/cistern diagram.

The underdrain pipe of the bioretention cells connects to a cylindrical cistern, where the effluent of the bioretention is stored. Two 0-9 m pressure loggers (ONSET HOBO Data Loggers) are installed in the cistern to measure (1) water pressure at the bottom of the cistern and (2) the local barometric pressure. The use of two pressure loggers allows accurate estimate of water level inside the cistern at any time. The water volume inside the cistern is calculated based on the shape of the cistern (Table 2.5.1).

The treated water from the cistern is provided to a nearby vegetable garden as a source of water and nutrients during the Spring, Summer, and Fall seasons. A water sample is taken from the cistern after each rain event or on a weekly basis for analysis (Sample 2 in Figure 2.2.1). This procedure can be done by attaching a cleaned plastic bottle (200 mL) at the end of an extension rod to reach the water inside the cistern. Similar to the procedure of handling sample 1, two cleaned plastic bottles (200 mL each) are used for water quality analyses. Beside water samples 1 and 2, tap water were also collected biweekly for water quality analyses. Two cleaned plastic bottles (200 mL each) were used to collect tap water from the environmental engineering laboratory of the Civil and Environmental Engineering Department, UMD.

## 2.3 Analytical Procedures

Water samples were taken to the UMD Environmental Engineering Laboratory and analyzed for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), heavy metals (Cu, Pb, and Zn), pH, and electrical conductivity (EC). The TSS, TN and TP analysis were conducted right away after the sample collection or within 10 days for the preserved samples (Table 1). The samples were preserved by adding 2 mL of concentrated trace-metal grade (Fisher Scientific) HCl/L of water sample for TP and heavy metals analyses, and by adding 2 mL of concentrated $H_2SO_4$/L of water sample for TN analysis, and stored in a freezer. The water quality analyses followed Standard Methods (Table 2.3.1).

### *2.3.1 TSS procedure*

The TSS testing is obtained from Standard Method 2540-D (APHA 2005). Well-mixed 100-mL unacidified water samples are poored into prepared glass-fiber filters

(Whatman type A/E with ϕ 47 mm) in vacuum filtration. A volume of 200 mL can be used instead of 100 mL to provide more accurate results.

### *2.3.2 TP procedure*

Water samples, preserved with HCl, are used to analyze for TP and other phosphorus speciation (dissolved phosphorus and phosphate). The TP analysis follows the Persulfate digestion method and colorimetric method by using ascorbic acid (4500-P B & E, APHA 2005) (Table 2.3.1). The standard solutions were produced from RICCA phosphorus standard, 1000 mg/L P. The digested samples were filtered by 0.22-μm filter paper to remove particulate matters that may interfere with the absorbance of UV light. The absorbance of digested water samples mixed with reagent is measured by a UV-vis recording spectrophotometer, SHIMADZU UV160U.

For dissolved phosphorus analysis, water samples are filtered by 0.22-μm filter paper to remove all particulate matters and then follow the TP procedure (4500-P B & E). For phosphate analysis, water samples were filtered and then follow the coloricmetric method only (no digestion).

### *2.3.3 TN procedure*

Water samples, preserved with $H_2SO_4$, are use to analyze for TN and other nitrogen species (nitrite, nitrate, and ammonium). The TN analysis is taken from Bachmann and Canfield Jr (1996) with a small modification in the procedure.  The standard stock solution is made directly from Fisher Scientific urea, $CH_4N_2O$ (FW = 60 g). Dissolving 1.07 g of urea in 1L of deionized water makes a 500-mg/L N stock solution. After the prepared sample and standard solutions were autoclaved (all nitrogen species are converted to $NO_3^-$), 0.2 mL of concentrated HCl instead of 0.2 mL concentrated $H_2SO_4$

was injected into each solution to provide more accurate result from Cary 60 UV-Vis spectrophotometer, Agilent Technologies. The absorbance of each solution is calculated based on standard method 4500-$NO^-_3$ B (APHA 2005).

A = absorb. (at 220 nm) – 2 x absorb. (at 275 nm) (Eq. 2.3.3)

For nitrite testing, 4500 $NO_2^-$ B method (APHA 2005) is used with color reagent. Water samples must not be acidified to provide accurate result. Stock nitrate solution of 500 mg/L is made by dissolving 2.464 g of $NaNO_2$ crystalline powder (SIGMA Life Science) in 1 L of deionized water. The final solutions from this method are measured at the wavelength of 543 nm in Cary 60 UV-Vis spectrophotometer, Agilent Technologies to estimate the concentration of water samples.

For nitrate testing, the 500 mg/L $NaNO_3$-N stock solution is made by dissolving 3.036 g of $NaNO_3$ crystalline (Fisher Scientific) in 1 L of deionized water. The standard solutions are diluted from prepared 500 mg/L $NaNO_3$-N stock solution. The standard solutions and water samples are placed into the Ion Chromatography Instrument (DIONEX ICS-1100) to measure for nitrate absorbance.

Unacidified water samples also were tested for ammonium via 4500 $NH_3$-N standard method (APHA 2005) with phenate method. Dissolving 1.911 g of ammonium chloride crystalline $NH_4Cl$ (Fisher Scientific) in 1 L of deionized water makes 500 mg/L-N ammonium chloride stock solution. The absorbance of final solutions is measured at 640-nm wavelength by the UV-vis recording spectrophotometer, SHIMADZU UV160U.

***2.3.4 pH and EC***

The pH of each fresh (non preserved) sample was measured using an Orion pH meter, model 520A. The pH meter was calibrated by using standard solutions at pH of 4, 7 and

10 (BDH pH reference standard buffers) before each use to obtain more precise measurement. The electrical conductance (EC) of the samples was measured using a YSI model 35 conductance meter, including the current temperature of the solution to support accurate EC calculation. The YSI 35 conductance meter is calibrated by measuring the conductance (mS) of a standard solution of NaCl (SIGMA Life Science).

### *2.3.5 Heavy Metals*

Unfiltered, acidified water samples were digested with concentrated trace-metal $HNO_3$ solution (Fisher Scientific) via Standard Method 3030-E (APHA 2005). Standard solutions are diluted from Calibration Standard 5, EPA Method 2000.7 (High-Purity Standards) with 2% trace-metal nitric acid. The prepared standard solutions and digested water samples are measured for Cu, Pb, and Zinc by using the ICPE-9000, SHIMADZU Plasma Atomic Emission Spectrometer. Lead is also measured at a more sensitive level by using the AA-7000A, SHIMADZU Graphite Furnace Atomizer.

**Table 2.3.1**: Standard Methods for Water Quality Analysis

| **Parameters** | **Analytical Method/ Instrumentation** | **Detection limit** | **Range** |
|---|---|---|---|
| TSS | 2540 D (APHA, 2005) | 1 mg/L | 200 mg/L |
| TP | 4500-P B.5, 4500-P E (APHA, 2005), UV160U SHIMADZU | 0.01 mg/L | 2 mg/L |
| TN | (Bachmann and Canfield 1996) | 0.01 mg/L | 5 mg/L |
| Cu, Zn | ICPE-9000, SHIMADZU | 1 µg/L | 500 µg/L |
| Pb | AA-7000A, SHIMADZU | 0.1 µg/L | 20 µg/L |
| pH | Orion pH Meter, Model 520A | 0.01 pH unit | |
| Electrical Conductance | Conductance Meter, YSI Model 35 | 0.1 µS/cm | 200,000 µS/cm |

## 2.4 Quality Control

Rigorous QA/QC was implemented through all processes of sample collection, storage and analysis. Glass bottles and testing equipment were washed with soap, tap water and DI water first, then acid washed (at least 10 hours), and then DI washed (3 times) before placement in the storage or the water sampler. Water samples were taken within 24 hours from the end of each rain event and transported to the University of Maryland Environmental Engineering Laboratory for analysis or preservation. All samples were tested right away or were sealed, labeled, and then placed in a refrigerator for later testing. Gloved-personnel were used at all time to handle, preserve, and test water samples to ensure no contamination occurred during these processes.

Duplicate standard solutions, standard addition, and duplicate water samples are used to ensure data quality. Duplicate standard solutions (often the median and the highest standard solutions) are used in each analytical method after the measurement of water samples. The difference in the result of the same standard solution shows the bias of the method. This bias can be caused by the system contamination after measuring a number of samples. Thus, a duplicate standard solution is used after measuring 5 to 10 water samples.

Standard addition method (or standard spike) is also applied to a particular sample to determine if there are any interferences of the sample to the analysis method. This method is done by adding a known amount of standard to a known volume of fresh sample, then both the original and the new samples are measured. The difference in the result will determine whether the sample caused any significant interference to the instrument. The standard addition method was used one time on both influent and cistern water samples for TP, TN, and heavy metal analyses to ensure the accuracy of the instruments; however, it also was used for influent samples if the concentration was lower than that of the cistern or below the detection limit.

Duplicate sampling is applied to indicate the stability of analytical methods. The difference in measured duplicate samples also shows the consistency of handling and preparing processes, the analytical methods, and the accuracy of instruments. This method was used several times on the analyses for heavy metals, especially lead, due to their low concentrations in stormwater runoff. For TP and TN, It was done one time to confirm any interferences.

The auto-sampler at the inlet of the bioretention may record false readings of the inflow runoff caused by leftover water ponding beneath the bubbler sensor, dirt and spider webs inside the sensor. The system recorded small flows into the system even when there was no flow. Thus, the bubbler tube and its level were checked monthly to clear out any obstacles and to maintain the accuracy.

### 2.5 Data Handling and Statistical Analyses

The cistern water levels were estimated based on the difference between the barometric pressure and the water absolute pressure. The water levels before and after a rain event were used to calculate the volume change of water in the cistern (cylindrical shape) (Figure 2.1.3). From Chow (1988):

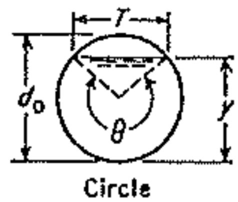



**Figure 2.5.1.** The cross-section view of a cylindrical cistern (Chow 1988).

$V_{Cistern} = A_{Cistern} * \text{Length} = \frac{1}{8} \times (\theta - \sin\theta)\, d^2 \times Length$ (Eq. 2.5.1)

With θ (rad) $= 2\pi - 2\cos^{-1}(\frac{h-r}{r})$

h or y: water level,

r: the radius of the cylindrical cistern,

d: the diameter of the cylindrical cistern,

θ (rad): the angle formed by the centerline to the water surface.

The equation above is used to estimate the water volume of the cistern at any water level. For example, if the pre- and post- water levels in the cistern are 0.1 m and 0.5 m respectively, then the difference in the post- and pre- volumes is 2.66 - 0.26 = 2.40 $m^3$, the volume gained from this rain event. Table 2.5.1 provides a quick estimate of water volume in the cistern and the volume gained based on certain water levels. The water level in the riser is often 0 unless the cistern is completely filled by treated water. The water volumes in the cistern and riser are calculated based on the designed parameters (Figure 2.1.3). The volume of water gained in the cistern (or $V_{Total}$) is the sum of $V_{Cistern}$ and $V_{Riser}$.

| $H_{Cistern}$ (m) | $H_{Riser}$ (m) | θ (rad) | $V_{Cistern}$ ($m^3$) | $V_{Riser}$ ($m^3$) | $V_{Total}$ ($m^3$) |
|---|---|---|---|---|---|
| 0.10 | 0.00 | 1.04 | 0.28 | 0.00 | 0.28 |
| 0.20 | 0.00 | 1.48 | 0.76 | 0.00 | 0.76 |
| 0.30 | 0.00 | 1.84 | 1.37 | 0.00 | 1.37 |
| 0.40 | 0.00 | 2.15 | 2.07 | 0.00 | 2.07 |
| 0.50 | 0.00 | 2.44 | 2.82 | 0.00 | 2.82 |
| 0.60 | 0.00 | 2.71 | 3.61 | 0.00 | 3.61 |
| 0.70 | 0.00 | 2.98 | 4.42 | 0.00 | 4.42 |
| 0.80 | 0.00 | 3.24 | 5.25 | 0.00 | 5.25 |
| 0.90 | 0.00 | 3.51 | 6.07 | 0.00 | 6.07 |
| 1.00 | 0.00 | 3.78 | 6.86 | 0.00 | 6.86 |
| 1.10 | 0.00 | 4.06 | 7.63 | 0.00 | 7.63 |
| 1.20 | 0.00 | 4.37 | 8.34 | 0.00 | 8.34 |
| 1.30 | 0.00 | 4.71 | 8.97 | 0.00 | 8.97 |
| 1.40 | 0.00 | 5.13 | 9.49 | 0.00 | 9.49 |
| 1.50 | 0.00 | 5.78 | 9.84 | 0.00 | 9.84 |
| 1.60 | 0.08 | 6.28 | 9.87 | 0.02 | 9.89 |
| 1.70 | 0.18 | 6.28 | 9.87 | 0.05 | 9.92 |
| 1.80 | 0.28 | 6.28 | 9.87 | 0.08 | 9.95 |
| 1.90 | 0.38 | 6.28 | 9.87 | 0.11 | 9.98 |
| 2.00 | 0.48 | 6.28 | 9.87 | 0.14 | 10.01 |
| 2.10 | 0.58 | 6.28 | 9.87 | 0.17 | 10.04 |
| 2.20 | 0.68 | 6.28 | 9.87 | 0.20 | 10.07 |
| 2.30 | 0.78 | 6.28 | 9.87 | 0.23 | 10.10 |
| 2.40 | 0.88 | 6.28 | 9.87 | 0.26 | 10.12 |
| 2.44 | 0.91 | 6.28 | 9.87 | 0.27 | 10.14 |

**Table 2.5.1**: Water level and water volume of the cylindrical cistern/riser.

Exceedance probability plots were used to evaluate the performance of the constructed bioretention. They were created by ranking the measured values from largest to smallest regardless of sample orders, and plotted on a log scale implying their log-normal distribution nature, as described by Li and Davis (2009). Technically, these exceedance probability plots do not show any relationships between influent and cistern concentrations of a certain rain event, but they help to see the removal efficiency of the facility.

# CHAPTER 3. RESULTS AND DISCUSSIONS

**3.1 Rainfall**

Table 3.1.1 shows the rainfall, measured runoff volume and theoretical runoff volume for all rain events from July 2014 to June 2015. These events have rainfall ranging from 0.03 to 7.67 cm. The runoff and theoretical runoff volumes were used to estimate the drainage area and the site abstraction volume.

Figure 3.1.1 shows that rainfalls of less than 0.2 cm generally generate minimal runoff (< 1000 L) to no runoff at all. These rain events are only sufficient to wet the drainage surface area and cause ponding water. The water abstraction of an area can be estimated based on the percentage of imperviousness, soil characteristics, and the site's slope. For any drainage area, the water abstraction volume is the difference between the rainfall volume (rainfall x drainage area) and the runoff volume entering the bioretention, which is approximately 8,500 liters for this drainage area. The relationship between the runoff volume and rainfall is expressed as:

$$y = 26041\,x - 8500 \text{ (Liters)}$$

(Figure 3.1.1) with x and y are the rainfall (cm) and runoff (L). An average effective drainage area of 2,604 ± 448 $m^2$ (~28,030 ± 4,822 $ft^2$) was estimated from the conversion of 26041 L/cm to $m^2$ (Figure 3.1.1). The 95% confidence interval of the drainage area is 2,156 to 3,052 $m^2$, indicates that this area is 16 to 64% (average of 40%) larger than the expected area of 1858 $m^2$ (~ 20,000 $ft^2$). This result also indicates extra runoff coming from adjacent grass areas (approximately 750 $m^2$ average or 8,000 $ft^2$) as shown in Figure 2.1.1.

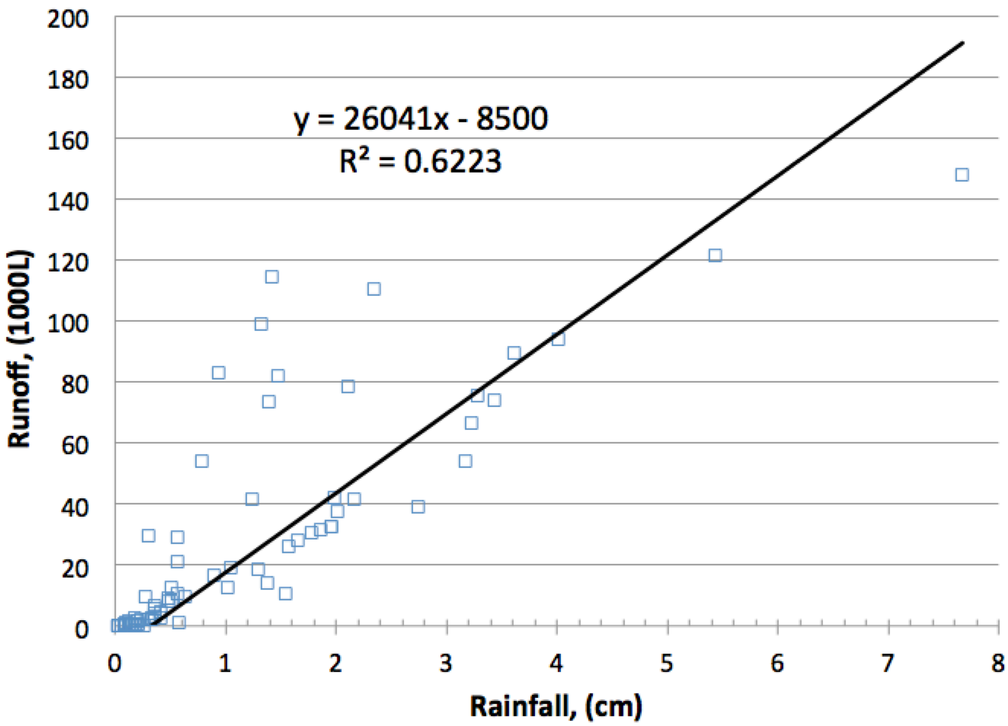



**Figure 3.1.1.** Runoff volume as a function of rainfall depth from July 2014 to June 2015 (Table 3.1.1) at the University of Maryland bioretention/cistern study site.

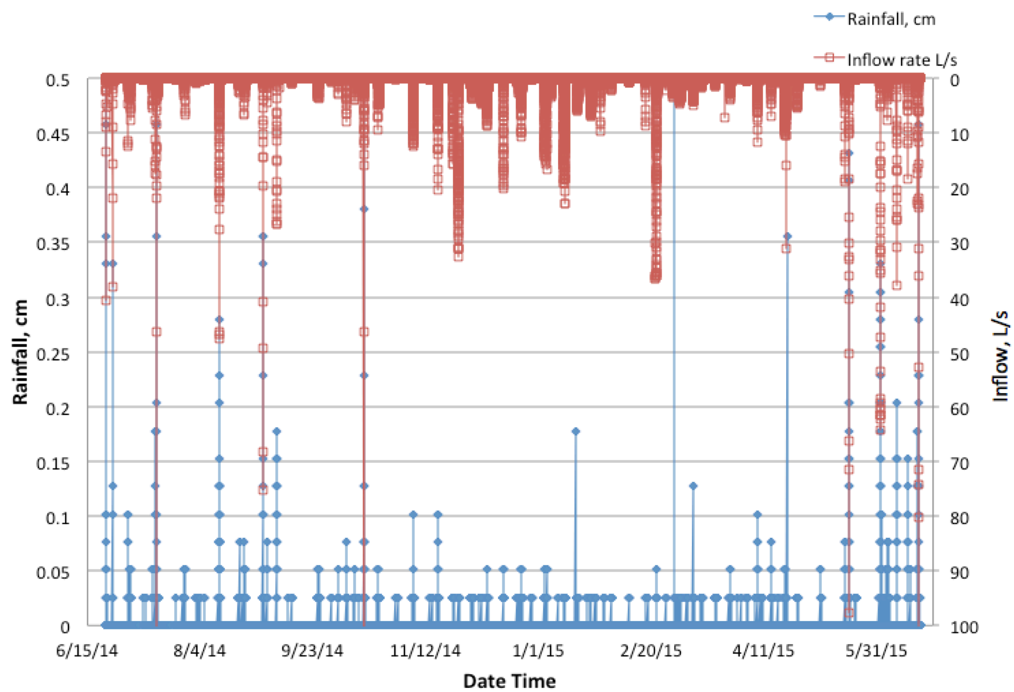
**Table 3.1.1:** Rainfall, runoff volume and theoretical runoff volumes of collected rain events.

| Date | Rainfall (cm) | Runoff Vol., (L) | Theor. Runoff, (L) |
|---|---|---|---|
| 2-Jul-14 | 0.51 | 1.28E+04 | 9.44E+03 |
| 3-Jul-14 | 0.89 | 1.67E+04 | 1.65E+04 |
| 10-Jul-14 | 0.18 | 2.69E+03 | 3.30E+03 |
| 13-Jul-14 | 0.51 | 8.35E+03 | 9.44E+03 |
| 14-Jul-14 | 0.56 | 1.05E+04 | 1.04E+04 |
| 15-Jul-14 | 3.61 | 8.97E+04 | 6.70E+04 |
| 24-Jul-14 | 0.03 | 2.83E+02 | 4.72E+02 |
| 27-Jul-14 | 0.41 | 4.79E+03 | 7.55E+03 |
| 1-Aug-14 | 0.36 | 5.83E+03 | 6.61E+03 |
| 3-Aug-14 | 0.13 | 1.78E+03 | 2.36E+03 |
| 6-Aug-14 | 0.08 | 5.10E+02 | 1.42E+03 |
| 12-Aug-14 | 5.44 | 1.22E+05 | 1.01E+05 |
| 20-Aug-14 | 0.36 | 4.25E+03 | 6.61E+03 |
| 21-Aug-14 | 0.20 | 1.81E+03 | 3.78E+03 |
| 23-Aug-14 | 0.48 | 9.20E+03 | 8.97E+03 |
| 31-Aug-14 | 0.64 | 9.60E+03 | 1.18E+04 |

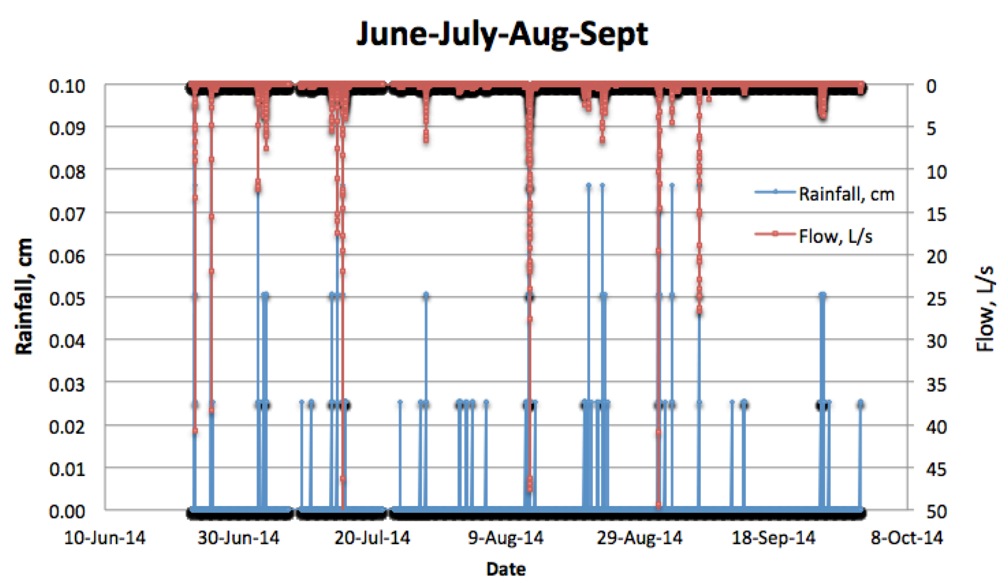
| | | | |
|---|---|---|---|
| 1-Sep-14 | 0.03 | 0 | 4.72E+02 |
| 2-Sep-14 | 0.41 | 2.78E+03 | 7.55E+03 |
| 6-Sep-14 | 2.01 | 3.78E+04 | 3.73E+04 |
| 11-Sep-14 | 0.03 | 0 | 4.72E+02 |
| 13-Sep-14 | 0.33 | 2.75E+03 | 6.14E+03 |
| 30-Sep-14 | 0.18 | 5.95E+02 | 3.30E+03 |
| 3-Oct-14 | 0.36 | 3.09E+03 | 6.61E+03 |
| 7-Oct-14 | 0.48 | 8.30E+03 | 8.97E+03 |
| 11-Oct-14 | 1.02 | 1.27E+04 | 1.89E+04 |
| 13-Oct-14 | 0.23 | 2.21E+03 | 4.25E+03 |
| 15-Oct-14 | 3.28 | 7.57E+04 | 6.09E+04 |
| 21-Oct-14 | 3.23 | 6.63E+04 | 5.99E+04 |
| 29-Oct-14 | 0.05 | 1.84E+02 | 9.44E+02 |
| 30-Oct-14 | 0.03 | 0 | 4.72E+02 |
| 5-Nov-14 | 0.94 | 8.29E+04 | 1.75E+04 |
| 13-Nov-14 | 0.10 | 4.81E+02 | 1.89E+03 |
| 16-Nov-14 | 0.13 | 6.80E+02 | 2.36E+03 |
| 17-Nov-14 | 2.11 | 7.84E+04 | 3.92E+04 |
| 23-Nov-14 | 0.79 | 5.41E+04 | 1.46E+04 |
| 2-Dec-14 | 3.18 | 5.41E+04 | 5.90E+04 |
| 6-Dec-14 | 1.47 | 8.20E+04 | 2.74E+04 |
| 9-Dec-14 | 1.32 | 9.89E+04 | 2.45E+04 |
| 16-Dec-14 | 1.04 | 1.90E+04 | 1.93E+04 |
| 22-Dec-14 | 0.36 | 6.40E+03 | 6.61E+03 |
| 24-Dec-14 | 1.96 | 3.26E+04 | 3.63E+04 |
| 25-Dec-14 | 0.28 | 9.60E+03 | 5.19E+03 |
| 29-Dec-14 | 0.10 | 1.16E+03 | 1.89E+03 |
| 3-Jan-15 | 1.42 | 1.15E+05 | 2.64E+04 |
| 4-Jan-15 | 0.30 | 2.96E+04 | 5.66E+03 |
| 12-Jan-15 | 1.78 | 3.06E+04 | 3.30E+04 |
| 17-Jan-15 | 0.18 | 0 | 3.30E+03 |
| 18-Jan-15 | 1.24 | 4.15E+04 | 2.31E+04 |
| 22-Jan-15 | 0.20 | 4.25E+02 | 3.78E+03 |
| 23-Jan-15 | 2.74 | 3.91E+04 | 5.10E+04 |
| 24-Jan-15 | 1.96 | 3.26E+04 | 3.63E+04 |
| 26-Jan-15 | 0.15 | 5.38E+02 | 2.83E+03 |
| 10-Mar-15 | 1.40 | 7.33E+04 | 2.60E+04 |
| 13-Mar-15 | 1.65 | 2.80E+04 | 3.07E+04 |
| 20-Mar-15 | 1.57 | 2.62E+04 | 2.93E+04 |
| 27-Mar-15 | 1.85 | 3.17E+04 | 3.45E+04 |
| 31-Mar-15 | 0.15 | 5.95E+01 | 2.83E+03 |

| | | | |
|---|---|---|---|
| 3-Apr-15 | 0.33 | 2.24E+03 | 6.14E+03 |
| 7-Apr-15 | 1.98 | 4.20E+04 | 3.68E+04 |
| 14-Apr-15 | 1.30 | 1.86E+04 | 2.41E+04 |
| 17-Apr-15 | 0.30 | 2.12E+03 | 5.66E+03 |
| 19-Apr-15 | 2.34 | 1.10E+05 | 4.34E+04 |
| 25-Apr-15 | 0.56 | 2.12E+04 | 1.04E+04 |
| 5-May-15 | 0.13 | 7.93E+02 | 2.36E+03 |
| 16-May-15 | 0.56 | 2.93E+04 | 1.04E+04 |
| 18-May-15 | 3.43 | 7.42E+04 | 6.37E+04 |
| 21-May-15 | 0.58 | 1.02E+03 | 1.09E+04 |
| 1-Jun-15 | 7.67 | 1.48E+05 | 1.43E+05 |
| 3-Jun-15 | 0.25 | 2.55E+02 | 4.72E+03 |
| 4-Jun-15 | 1.55 | 1.07E+04 | 2.88E+04 |
| 5-Jun-15 | 0.20 | 5.97E+02 | 3.78E+03 |
| 8-Jun-15 | 2.16 | 4.18E+04 | 4.01E+04 |
| 14-Jun-15 | 1.37 | 1.40E+04 | 2.55E+04 |
| 17-Jun-15 | 4.01 | 9.38E+04 | 7.46E+04 |

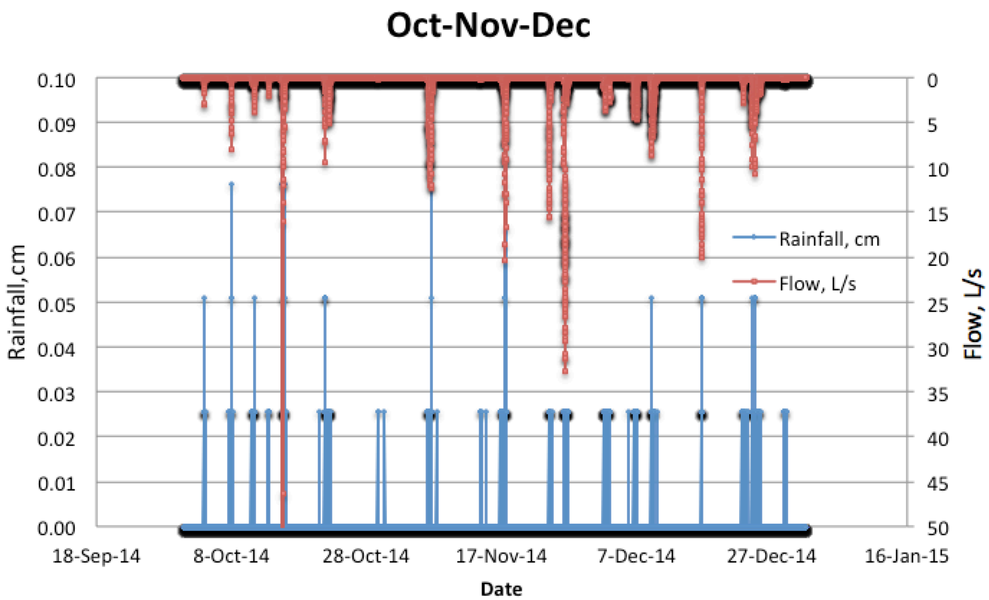
The responses between rainfall and runoff are presented in Figure 3.1.2. Overall, the data showed a reasonable response between rainfall and runoff because the runoff appeared after a sufficient amount of rainfall was recorded, when the major part of the drainage area is saturated. Because a major portion (> 99%) of the drainage area is impervious (parking area), there are some runoff events even when the soil is not completely saturated. In February 2015, a large runoff event occurred with a small rainfall. This phenomenon happened often during winter season when snowmelts were significant. Figure 3.1.2 indicates whether the drainage area has any snow melt events (no indication from the rain gauge in February 2015), rainfall (with indication from the rain gauge) or water leak from nearby buildings (no indication of rainfall).



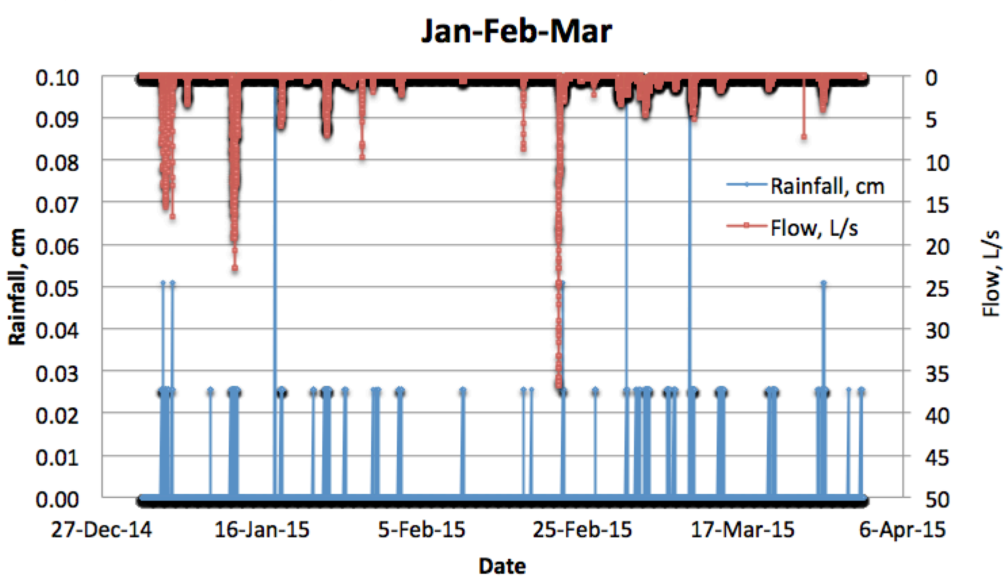

**a.** Plot for rainfall and inflow runoff for the University of Maryland bioretention study.



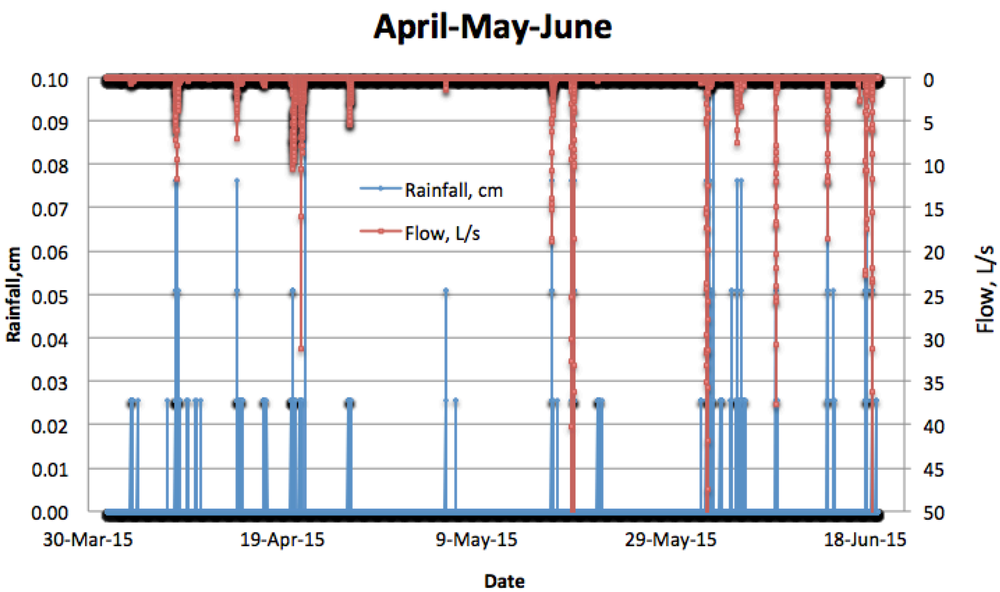

b. Plot for rainfall and inflow runoff from June to September 2014 for the University of Maryland bioretention study.




c. Plot for rainfall and inflow runoff from October to December 2014 for the University of Maryland bioretention study.




d. Plot for rainfall and inflow runoff from January to March 2015 for the University of Maryland bioretention study.




e. Plot for rainfall and inflow runoff from April to June 2015 for the University of Maryland bioretention study.
**Figure 3.1.2**. Overall rainfall and runoff flowrate response.

Figure 3.1.3 shows that small rain events generate less runoff because these rains need to saturate the soil (drainage water abstraction) first before it runs off. These data points lie below the 1:1 ratio line because the actual runoff is much less than the corresponding theoretical runoff. For large storm events, the actual runoff is often larger than the theoretical runoff. This can be explained by (1) false readings of the bubbler sensor (2) inaccurate flow equation and (3) possible runoff from adjacent areas. Generally, at the start and the end of a rain event, the water level in the flume is generally low (< 3.05 cm); hence, the estimated runoff is often larger than the theoretical runoff due to the inaccuracy of Equation 2.2.1 for low flows.

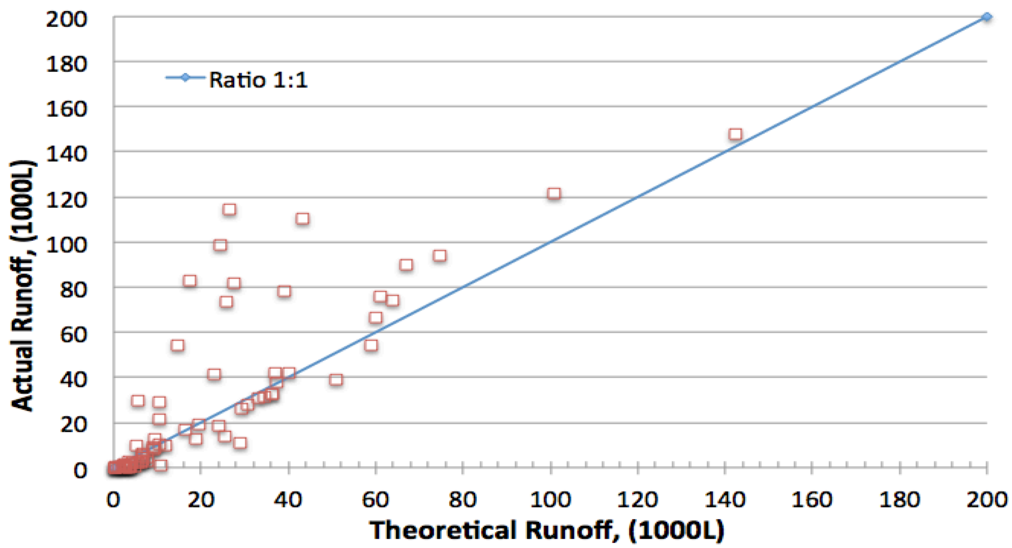



**Figure 3.1.3.** Actual runoff compared to theoretical runoff (rainfall x drainage area of 1,858 $m^2$) from July 2014 to June 2015 (Table 3.1.1) at the University of Maryland bioretention/cistern study.

### 3.2 Hydrology/Bioretention

The abstraction of the bioretention cell itself plays an important role in reducing the runoff effluent volume from the system. This abstraction depends on the design parameters and the media characteristics. The abstraction of this SCM, the difference between runoff volume, overflowed volume and cistern volume, can be seen clearly in Table 3.2.1 and Figure 3.2.2. The abstraction volume is estimated, by calculating the average bioretention abstraction volume (BAV) and the bowl volume (Davis et al. 2011). For underdrained bioretention:

Avg. BAV = RZMS x (SAT – WP) + LMS x (SAT – FC) (Eq. 3.2.1)

High BAV = Bowl Vol. + [RZMS x (SAT – WP) + LMS x (SAT – FC)] (Eq. 3.2.2)

With RZMS: root zone media storage

SAT: saturation

WP: wilting point

LMS: lower media storage

FC: field capacity

By assuming the bioretention media is sandy loam (WP = 8.0%, FC = 18.0%, and Sat = 45%) (Saxton and Rawls 2006), the site abstraction and the average bioretention abstraction volumes are estimated to be 8,500 L (Figure 3.1.1) and 4,378 L (Table 3.2.1), respectively, with a bowl volume of 895 L; this indicates that rain events of more than 0.45 cm (or 8.50 $m^3$/ 1858 $m^2$) are necessary to produce runoff and more than 0.75 cm (or (8.50 + 4.38 + 0.89) $m^3$/ 1858 $m^2$) will produce system overflow. The overflow is minimized when the rainfall intensity (cm/h) is smaller than the filtration rate. In this case, water level in the last bioretention cell decreases, indicating more water entering the cistern and less overflow volume. The bowl volume of cell 1 and 2 are not applicable in Table 3.2.1 because the surface level of these bioretention cells with the rip-rap section are relatively the same; the inflow runoff tends to move downstream instead of ponding in cell 1 and 2.

**Table 3.2.1:** Bioretention characteristics and BAV

| **Bioretention Characteristics** | **Cell 1** | **Cell 2** | **Cell 3** | **Total, ($m^3$)** |
|---|---|---|---|---|
| LMS (m) | 0.31 | 0.31 | 0.31 | |
| RZMS (m) | 0.31 | 0.31 | 0.31 | |
| Surface Area, ($m^2$) | 10.81 | 5.76 | 5.87 | 22.44 |
| Media Depth, (m) | 0.61 | 0.61 | 0.61 | |
| Volume of Media, ($m^3$) | 6.59 | 3.51 | 3.58 | 13.68 |
| Avg. BAV, ($m^3$), Eq. 3.2.1 | 2.11 | 1.12 | 1.15 | 4.38 |
| Overflow Level, m | | | 0.15 | |
| Bowl Volume, ($m^3$) | N/A | N/A | 0.89 | 0.89 |
| | | | Max. BAV | 5.27 |

The response of water level in the cistern to the rainfall from August 2014 to June 2015 is shown in Figure 3.2.1. This figure shows how much rain is needed for the cistern to gain water. For example in February 2015, when the rainfall increased from 0.1 to 1.0 cm, the cistern water level increased from 25 to 100 cm and kept increasing to 150 cm as more rainfall coming. When the runoff flow rate exceeds the infiltration rate of the bioretention cell, the water level increases in the bioretention cell storage to a certain level (a certain water pressure), water is forced through soil media and flows to the cistern (Davis et al. 2011). At this point, overflow may occur because water level reaches the overflow cage. Generally, the water level in the cistern starts increasing after a certain amount of rainfall/runoff. If the rainfall is small (< 0.75 cm) and spreads over a large time frame (2 hours in average) or less than 0.06 cm/10 minutes rainfall (e.g. November 2014 and January 2015), then there will not be any effluent from the bioretention facility because the inflow will be able to infiltrate and stay within the soil media. The cistern water levels before February 2015 were estimated based on the barometric pressure data taken from The Weather Underground Website (station at 38.982 Lat and -76.953 Long) and the water pressure at the bottom of the cistern. The cistern water level data after February 2015 are available as the second pressure probe came online.

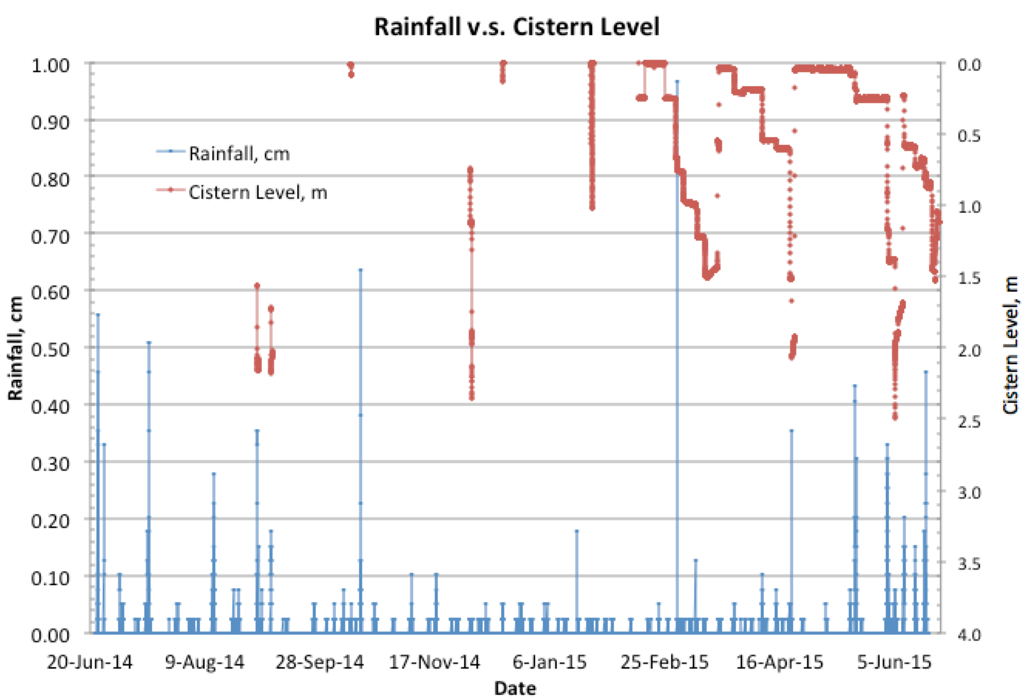



**FIGURE 3.2.1.** Plot for rainfall and water level in the cistern for the University of Maryland bioretention study.

The monthly water balance of this project is shown in Figure 3.2.2. For a rain event, the water balance data can be used to calculate the current site abstraction volume (as mentioned in the Rainfall section). Additionally, it is used to estimate the overflow volume. For example, the 1.63-cm rain event (lasting 11 hours) on March 14th shows $V_{Rainfall}$ of 30,700 L, runoff of 28,000 L, and the cistern gain of 963 L (Figure 3.2.2a). Then:

Overflow = Runoff – High BAV – Cistern gained = 28,000 – (4378 + 895) – 963

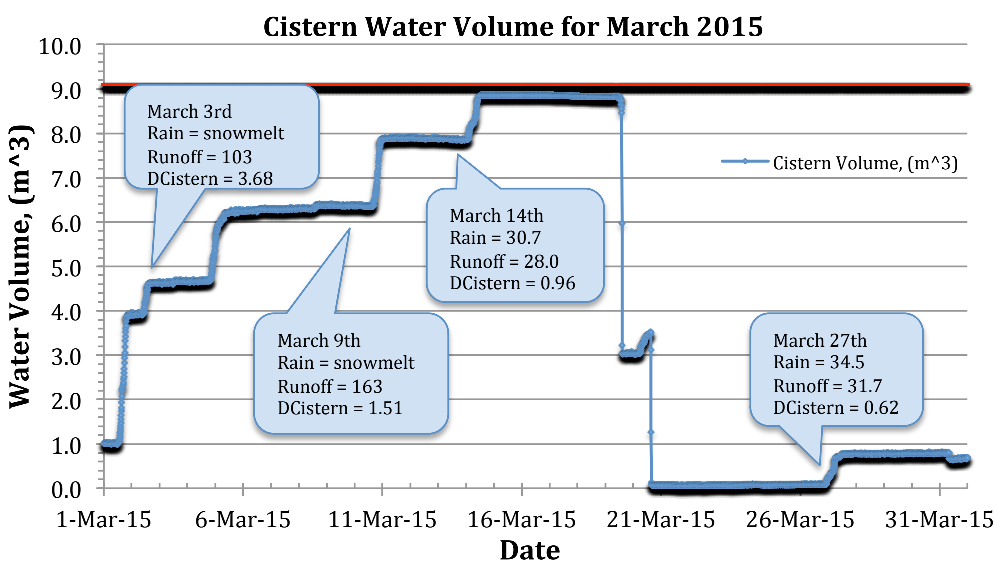
= 21,764 L

This rain event shows a large overflow volume caused by flow over the saturated bioretention cell and intense rainfall during the event. Moreover, Table 3.2.2 shows that the rainfalls on April 25th and May 21st, 2015 are 0.56 and 0.58 cm respectively. The rainfall values are almost the same, but event on April 25th generated an overflow volume of 15.94 $m^3$ while it is zero for event on May 21st. Thus, rain duration is a key to overflow volume. Based on the new estimated drainage area of 2,604 $m^2$, the bioretention facility is undersized (22.44 $m^2$/2604 $m^2$ = 0.86%). Large rainfall intensity (rainfall of greater than 0.75 cm in 2 hours) will cause overflow at the final cell. Moreover, if the rain duration is too short (e.g. < 1 hour), a rainfall of less than 0.75 cm may still cause overflow at the bioretention 3rd cell. The event on June 4th did not have a correct value for the cistern because it was full (the water volume reached the maximum allowable storage) during the rain event. The cistern was full because the pump was not operational before and during that event to recirculate existing treated water.

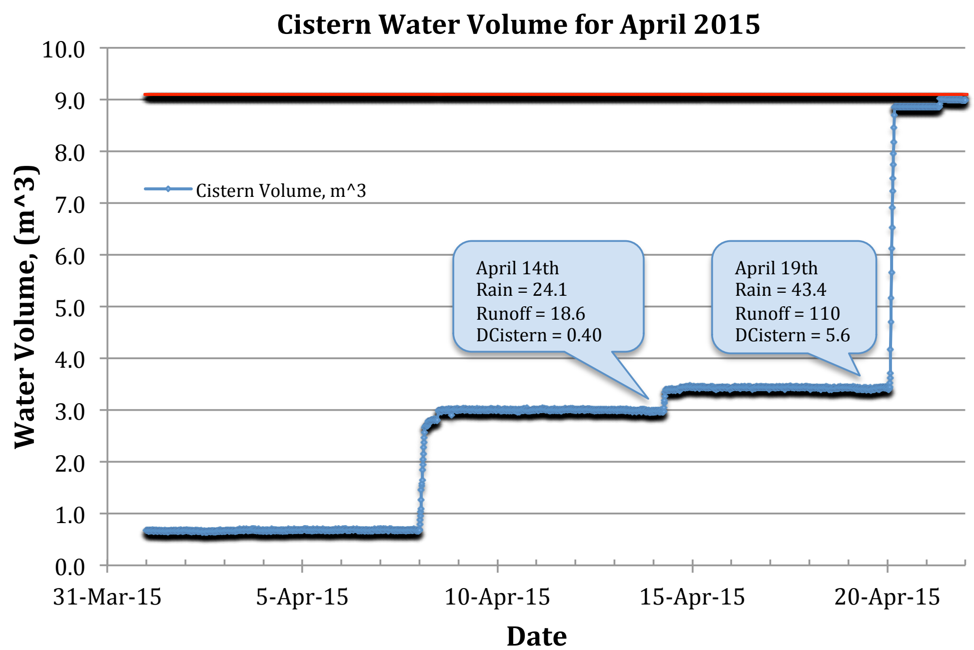
**Table 3.2.2:** Overflow volume for rain events from March to June 2015 for the University of Maryland bioretention study.

| Date | Rainfall (cm) | Runoff Vol. ($m^3$) | High BAV ($m^3$) | Cistern ($m^3$) | Overflow ($m^3$) |
|---|---|---|---|---|---|
| 10-Mar-15 | 1.40 | 73.34 | 5.27 | 1.51 | 66.56 |
| 13-Mar-15 | 1.65 | 28.01 | 5.27 | 0.96 | 21.77 |
| 20-Mar-15 | 1.57 | 26.25 | 5.27 | 0.45 | 20.53 |
| 27-Mar-15 | 1.85 | 31.66 | 5.27 | 0.63 | 25.76 |
| 31-Mar-15 | 0.15 | 0.06 | 5.27 | 0.00 | 0.00 |
| 3-Apr-15 | 0.33 | 2.24 | 5.27 | 0.00 | 0.00 |
| 7-Apr-15 | 1.98 | 42.02 | 5.27 | 2.35 | 34.40 |
| 14-Apr-15 | 1.30 | 18.58 | 5.27 | 0.40 | 12.90 |
| 17-Apr-15 | 0.30 | 2.12 | 5.27 | 0.00 | 0.00 |
| 19-Apr-15 | 2.34 | 110.32 | 5.27 | 5.60 | 99.46 |
| 25-Apr-15 | 0.56 | 21.21 | 5.27 | 0.00 | 15.94 |

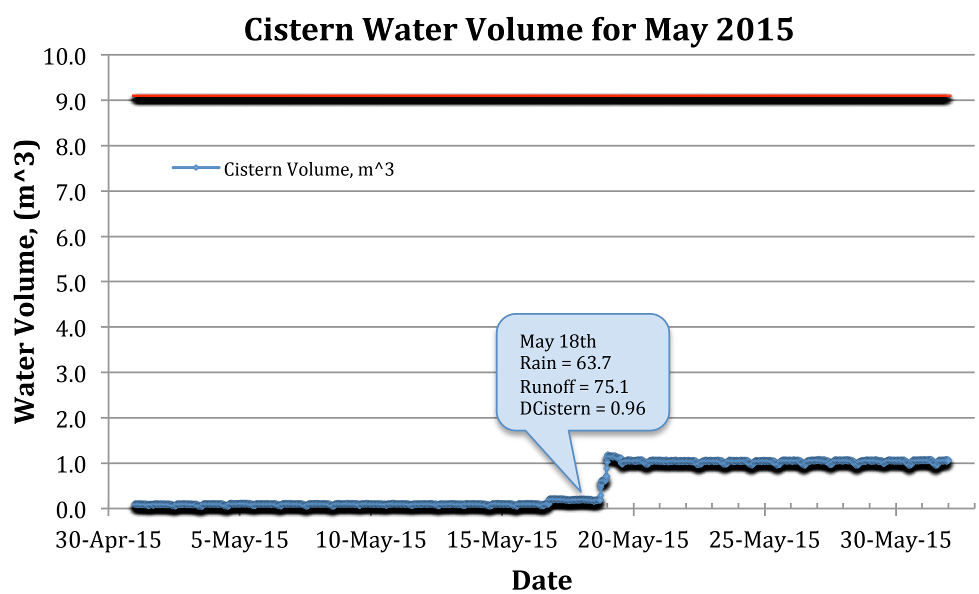
| | | | | | |
|---|---|---|---|---|---|
| 5-May-15 | 0.13 | 0.79 | 5.27 | 0.00 | 0.00 |
| 16-May-15 | 0.56 | 29.34 | 5.27 | 0.09 | 23.98 |
| 18-May-15 | 3.43 | 74.22 | 5.27 | 0.98 | 67.97 |
| 21-May-15 | 0.58 | 1.02 | 5.27 | 0.00 | 0.00 |
| 1-Jun-15 | 7.67 | 147.93 | 5.27 | 7.66 | 135.00 |
| 3-Jun-15 | 0.25 | 0.25 | 5.27 | 0.00 | 0.00 |
| 4-Jun-15 | 1.55 | 10.70 | 5.27 | 0.51 | 4.92 |
| 5-Jun-15 | 0.20 | 0.60 | 5.27 | 0.00 | 0.00 |
| 8-Jun-15 | 2.16 | 41.77 | 5.27 | 2.34 | 34.16 |
| 14-Jun-15 | 1.37 | 14.02 | 5.27 | 1.01 | 7.74 |
| 17-Jun-15 | 4.01 | 93.81 | 5.27 | 1.45 | 87.09 |



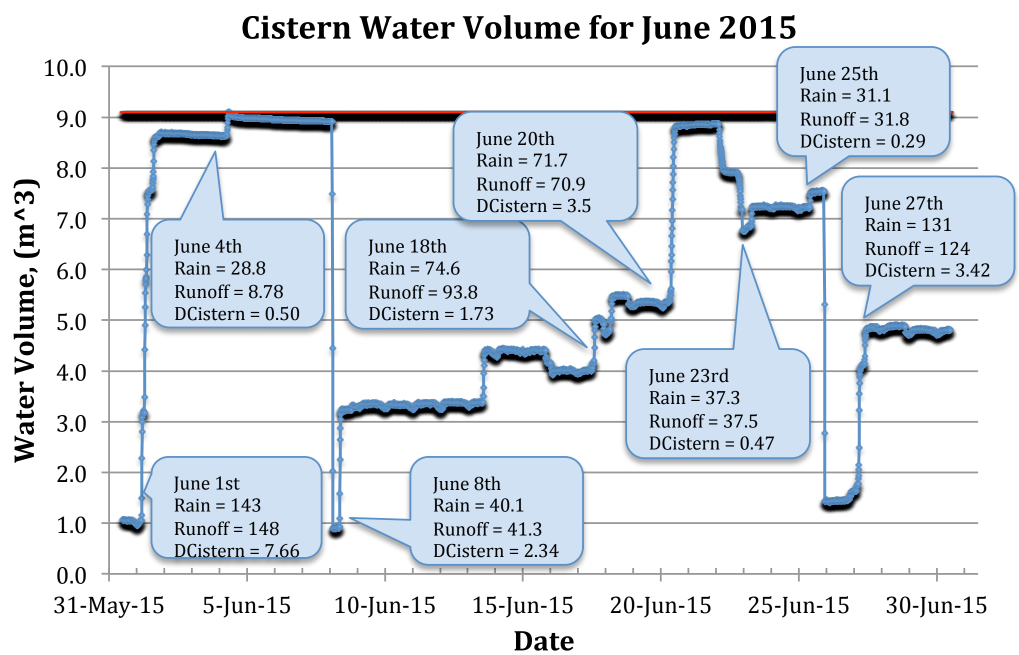

a.


Cistern Water Volume for April 2015
Water Volume, (m^3)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Cistern Volume, m^3
April 14th
Rain = 24.1
Runoff = 18.6
DCistern = 0.40
April 19th
Rain = 43.4
Runoff = 110
DCistern = 5.6
31-Mar-15
5-Apr-15
10-Apr-15
15-Apr-15
20-Apr-15
Date

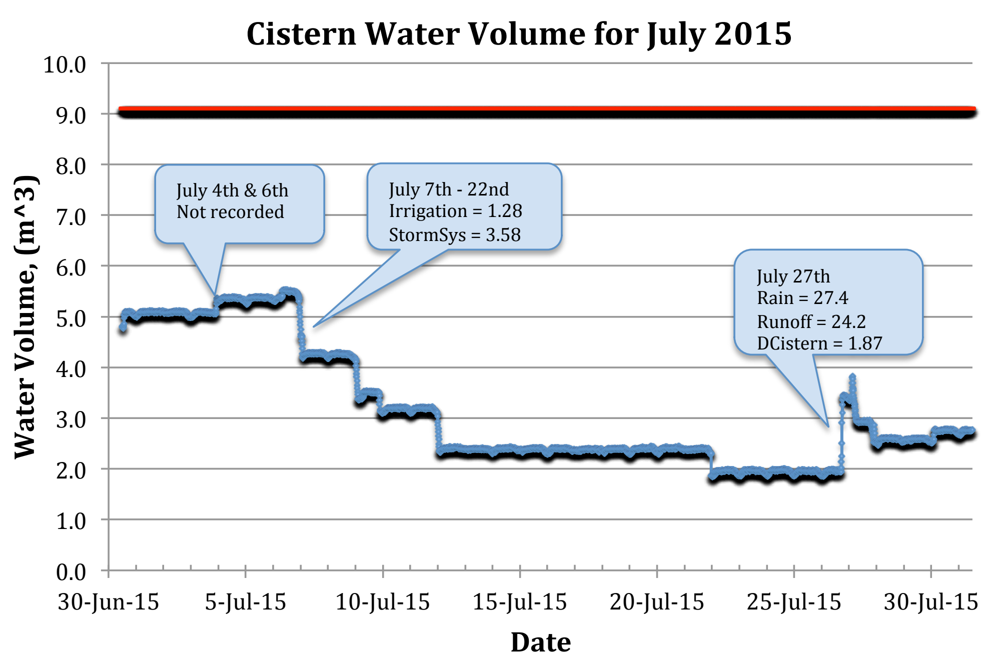
b.


Cistern Water Volume for May 2015
Water Volume, (m^3)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Cistern Volume, m^3
May 18th
Rain = 63.7
Runoff = 75.1
DCistern = 0.96
30-Apr-15
5-May-15
10-May-15
15-May-15
20-May-15
25-May-15
30-May-15
Date

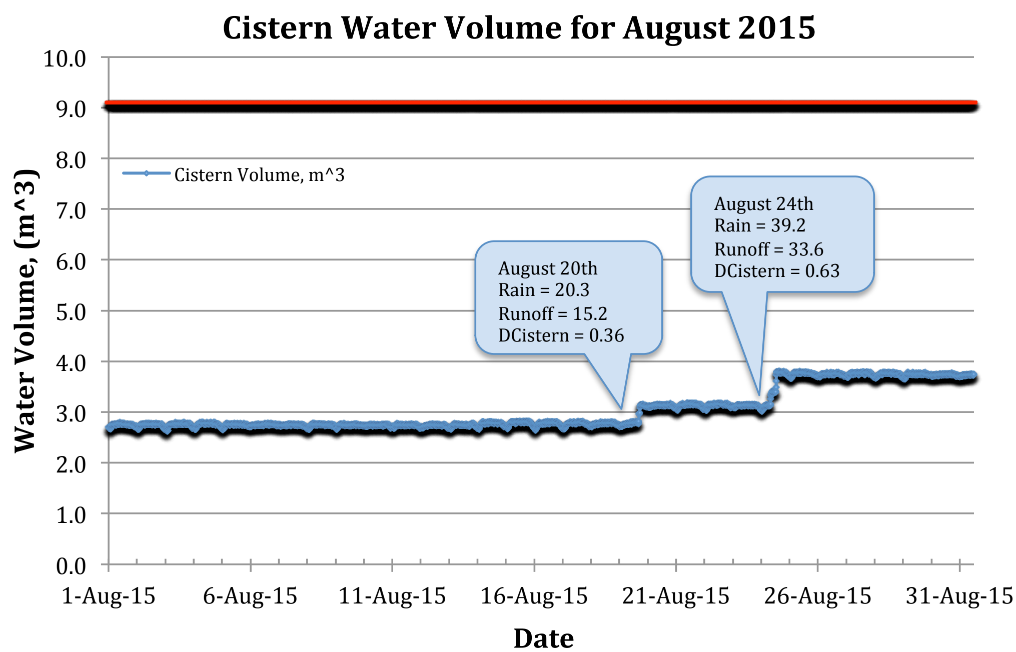
c.


Cistern Water Volume for June 2015
Water Volume, (m^3)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
31-May-15
5-Jun-15
10-Jun-15
15-Jun-15
20-Jun-15
25-Jun-15
30-Jun-15
Date
June 1st Rain = 143 Runoff = 148 DCistern = 7.66
June 4th Rain = 28.8 Runoff = 8.78 DCistern = 0.50
June 8th Rain = 40.1 Runoff = 41.3 DCistern = 2.34
June 18th Rain = 74.6 Runoff = 93.8 DCistern = 1.73
June 20th Rain = 71.7 Runoff = 70.9 DCistern = 3.5
June 23rd Rain = 37.3 Runoff = 37.5 DCistern = 0.47
June 25th Rain = 31.1 Runoff = 31.8 DCistern = 0.29
June 27th Rain = 131 Runoff = 124 DCistern = 3.42

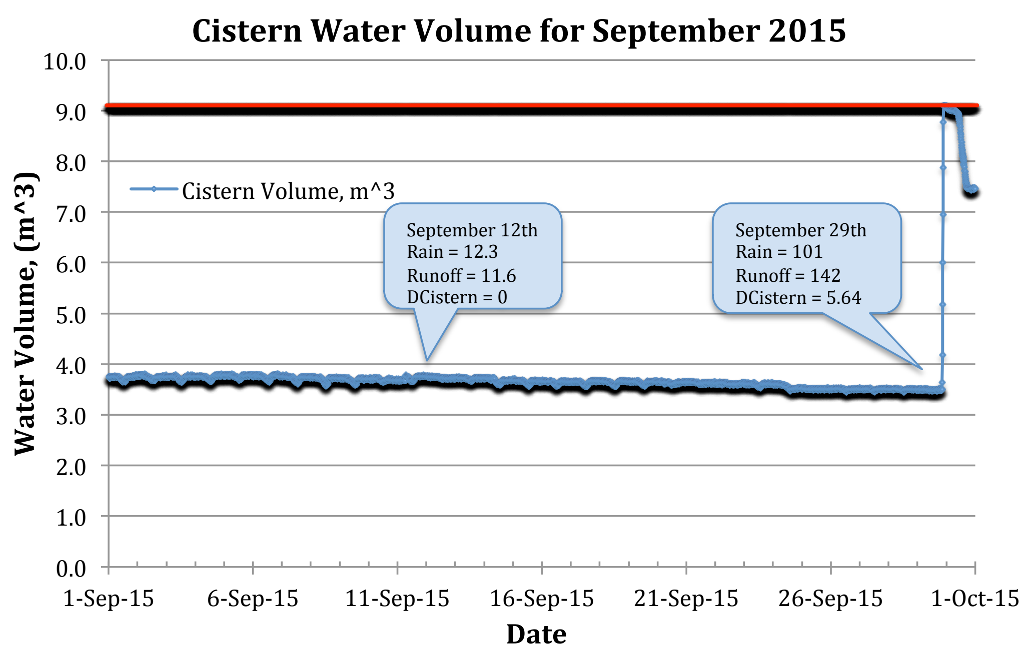
d.


Cistern Water Volume for July 2015
Water Volume, (m^3)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
30-Jun-15
5-Jul-15
10-Jul-15
15-Jul-15
20-Jul-15
25-Jul-15
30-Jul-15
Date
July 4th & 6th Not recorded
July 7th - 22nd Irrigation = 1.28 StormSys = 3.58
July 27th Rain = 27.4 Runoff = 24.2 DCistern = 1.87

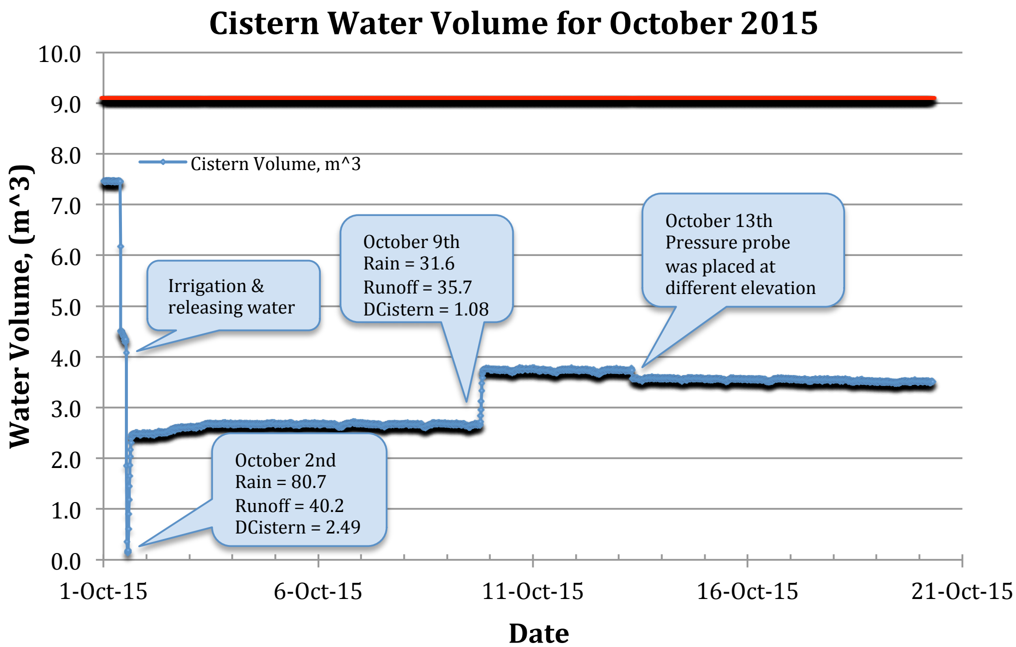
e.


Cistern Water Volume for August 2015
Water Volume, (m^3)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Cistern Volume, m^3
August 20th
Rain = 20.3
Runoff = 15.2
DCistern = 0.36
August 24th
Rain = 39.2
Runoff = 33.6
DCistern = 0.63
1-Aug-15
6-Aug-15
11-Aug-15
16-Aug-15
21-Aug-15
26-Aug-15
31-Aug-15
Date

f.


Cistern Water Volume for September 2015
Water Volume, (m^3)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Cistern Volume, m^3
September 12th
Rain = 12.3
Runoff = 11.6
DCistern = 0
September 29th
Rain = 101
Runoff = 142
DCistern = 5.64
1-Sep-15
6-Sep-15
11-Sep-15
16-Sep-15
21-Sep-15
26-Sep-15
1-Oct-15
Date

g.




h.
**Figure 3.2.2**. Monthly cistern water volume from March to October 2015 (a-h) with Rain (rainfall volume), Runoff (runoff volume), and DCistern (volume gained in the cistern) in $m^3$ and the cistern volume is 9.1 $m^3$.

The time for the runoff to infiltrate through bioretention media (from runoff to cistern) from March 10$^{th}$ to October 10$^{th}$ is shown in Figure 3.2.3. The average was 107 ± 58 minutes; the filtration time varies significantly from a minimum of 7 minutes to a maximum of 708 minutes, with the 95% confidence interval of 49 to 165 minutes. This variation depends on the moisture content of the bioretention media and rainfall intensity. The rain event on March 13$^{th}$, 2015, that had 708 minutes of filtration time, was a moderate rainfall (1.65-cm rainfall) spread uniformly over a long rain duration (~ 17 hours) that caused runoff to stay and slowly infiltrate through media (little water pressure) (Table 3.2.2). Conversely, the 7-minute duration on April 14$^{th}$, 2015 resulted from a rain event (1.3-cm rainfall in 14.5 hours) was very intense (0.7-cm rainfall during the first 70 minutes); the water pressure is high in the bioretention cells, forcing water to percolate through soil media quickly.

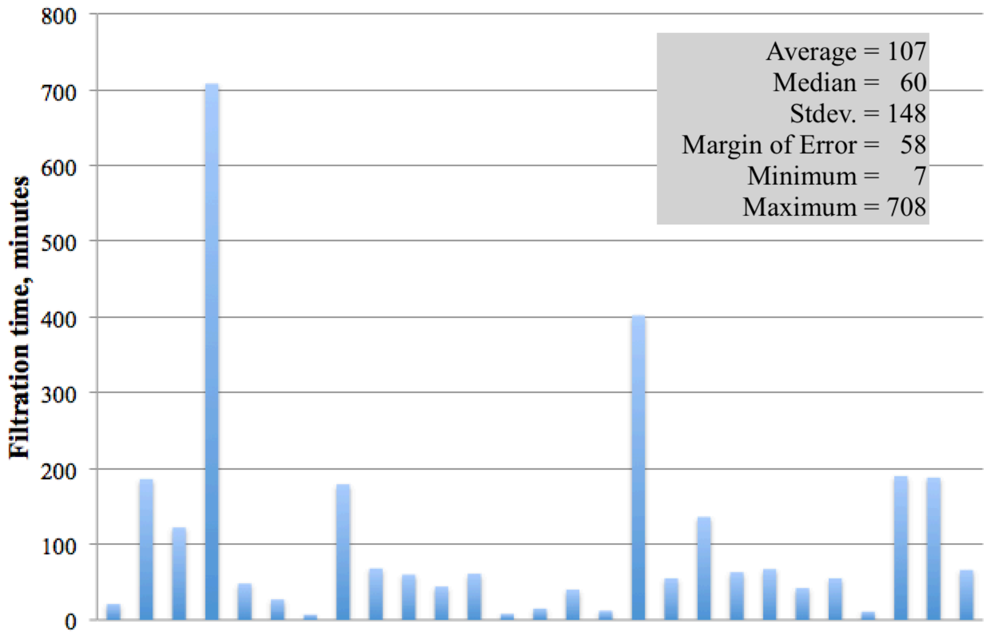



**Figure 3.2.3**. The estimated time for the runoff to infiltrate through bioretention media of rain events from March 10th to October 10th 2015.

A summary of stormwater runoff volume between March 10th and November 10th is shown in Figure 3.2.4. With a total runoff volume of 1,260 $m^3$, approximately, 89% of it is overflow volume, 8% bioretention storage, and 3% cistern storage (including irrigation portion). The overflow volume accounts for a major portion of the runoff volume because the bioretention facility is undersized (< 1% of drainage area). Having larger fractions of outflow volume due to undersized bioretention has been reported for a field study in North Carolina (Brown and Hunt 2011). The irrigation volume (from the cistern) is less than 1% of the runoff or 6% of the cistern volume, indicating more water is available for irrigation.

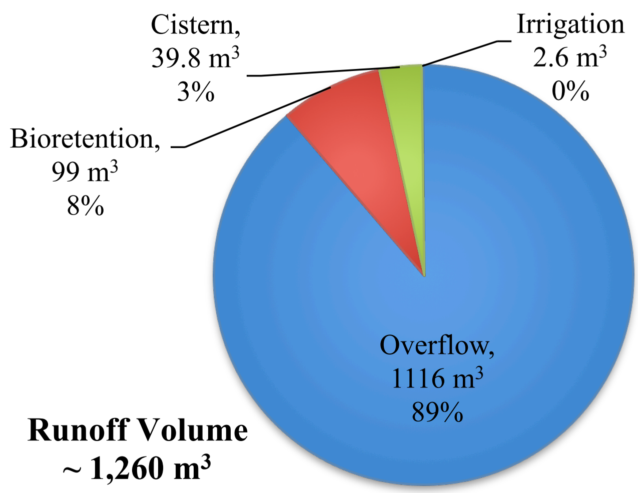



**Figure 3.2.4**. Stormwater partition from March 10th to November 10th, 2015 for the University of Maryland bioretention study.

### 3.3 Water quality

Twenty-seven composite water sample sets (inflow and cistern) from 27 rainfall events were successfully collected and analyzed for TSS and TP, but only 24 sample sets were analyzed for TN. Figure 3.3 shows water samples (Left = Runoff, Right = Cistern) of rain event on October 28, 2015. To evaluate water quality performance for bioretention, a consideration of the output water quality, regardless of the input concentrations and their correspondent removals, is shown in probability plots. Using probability plots to express water quality data is recommended by Strecker *et al.* (2001) because they provide several advantages in analyzing the obtained data sets. First, the similarities and differences among data sets can be easily visualized. Second, median value and values at various percentiles are noticeable clearly. Finally, the exceedence probability and the total maximum daily load (TMDL) of the target parameters can be evaluated directly for all obtained data sets.

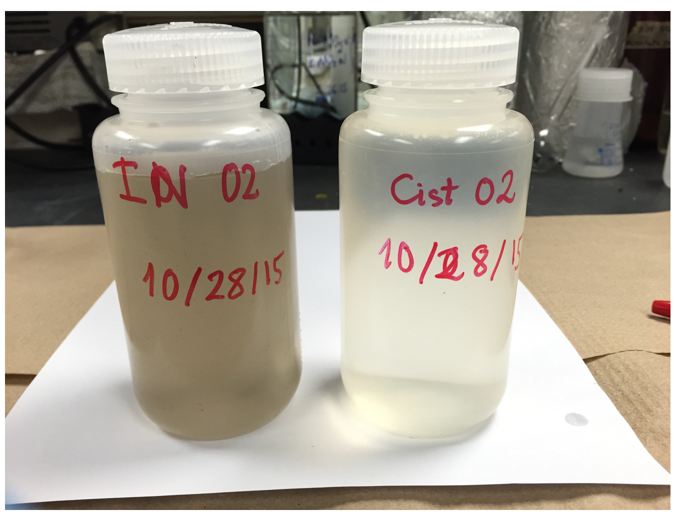



**Figure 3.3**. Well-mixed water samples (200 mL) (Left bottle = Runoff, Right bottle = Cistern) of rain event on October 28$^{th}$ 2015 for the University of Maryland bioretention study.

### *3.3.1 Total Suspended Solids*

TSS analysis shows that the inflow concentrations of suspended solids range from 50 to 389 mg/L with the average of 164 ± 104 mg/L (Figure 3.3.1). The influent TSS concentrations are found to be similar with other field studies; such as, 100 mg/L in Li and Davis (2014), discrete TSS concentrations from 5.3 to 1274 mg/L with the median of 76 mg/L (Liu and Davis 2014), EMC median of 34 mg/L (Davis 2007), and the mean of 49.5 mg/L (Hunt et al. 2008). At 50% exceedance probability, the median TSS concentration is around 120 mg/L (Figure 3.3.1b). The influent TSS varied significantly between rain events due to possible soil erosion (large rainfall intensity) and nearby construction stockpiles near the site.

The TSS concentrations in the cistern are reasonably consistent but may not show the true TSS in the cistern because some sedimentation may occur in the cistern within several hours. Therefore, 10 mg/L TSS was found many times in cistern water samples. The cistern TSS concentrations range from 1 to 40 mg/L with the mean of 14 ± 10.3 mg/L. Comparing to the TSS effluent concentration of 7.4 mg/L (Li and Davis 2014), EMC median of 18 mg/L (Davis 2007), discrete concentration from 0.5 to 99 mg/L with the median of 4.6 mg/L (Liu and Davis 2014), the mean of 20.0 mg/L (Hunt et al. 2008), and EMC of < 20 mg/L at 50% probability (Fassman 2012), the average of 14 mg/L in the cistern is a reasonable TSS level for the effluent of a standard bioretention cell. At 50% exceedance probability, the median TSS concentration is around 10 mg/L for the cistern. The solar pump may not disturb this layer of sediment, thus, the TSS in the cistern is not a concern for irrigation. The TSS removal percentage ranges from 78% to 99%, which is efficient and reasonable for bioretention from other studies.

The probability plots for the inflow and cistern values have a similar large slope, showing a significant variation in TSS concentration (Figure 3.3.1b). The t-test (2 tails) shows that null hypothesis is rejected at the level of p=0.05. This means that the influent and cistern TSS concentrations are significantly different, showing possible TSS removal of the bioretention facility (Figure 3.3.1a). The Wilcoxon rank-sum test evaluation found that TSS concentrations were significantly removed by the bioretention system at $\alpha$ = 5%. The results indicate good filtration performance of bioretention cells.

Filtration is the removal mechanism for the TSS (Davis et al. 2009; Zhang and Guo 2014). As the inflow percolates through the bioretention soil media, any particulate matter larger than the media pore size is retained at the surface of bioretention cell (LeFevre et al. 2014).

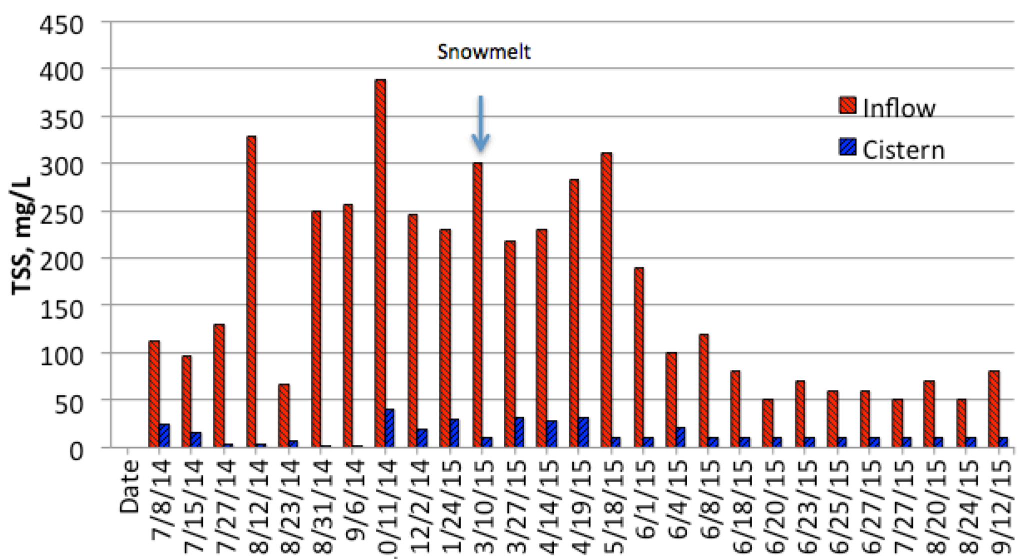



**Figure 3.3.1a**. TSS concentration of 27 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

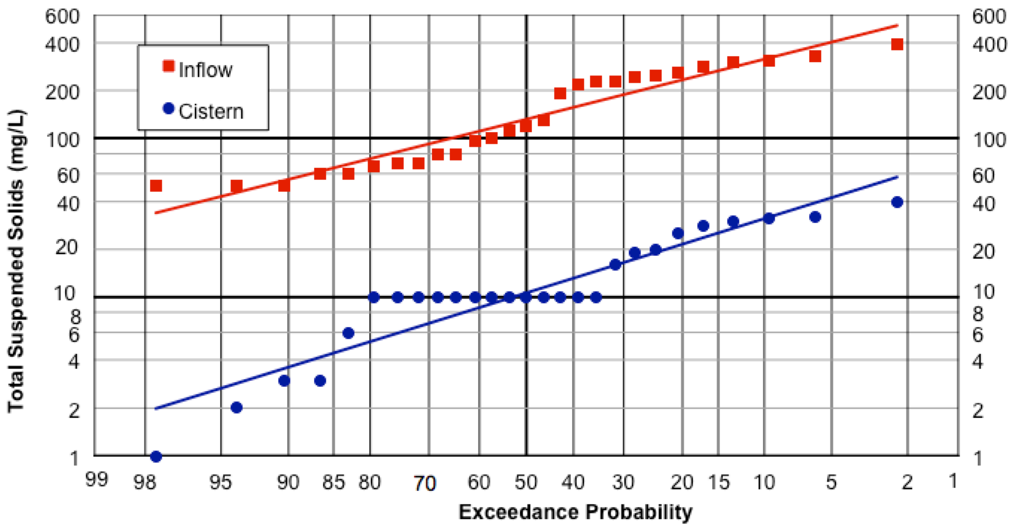



**Figure 3.3.1b.** Probability plot for total suspended solids concentration (27 samples) for the University of Maryland bioretention study.

### *3.3.2 Total Phosphorus/Phosphorus Speciation*

*3.3.2.1 Total Phosphorus*

From Table 3.3.2.1, the inflow has the average of 0.53 ± 0.32 mg/L TP, ranging from 0.17 to 1.68 mg/L. The concentrations are close to other field studies, EMC median of 0.21 mg/L (Liu and Davis 2014), EMC of 0.61 mg/L (Davis 2007), 0.19 mg/L (Hunt et al. 2008), and 0.14 ± 0.1 mg/L (Passeport et al. 2009). The probability plot for the inflow values has a larger slope than the cistern values, showing that the influent TP concentrations vary within a larger range (0.2 to 1.2 mg/L) than the cistern (0.06 to 0.3 mg/L) (Figure 3.3.2.1b). At 50% exceedance probability, the TP concentration is around 0.42 mg/L (Figure 3.3.2.1b), within 1 standard deviation of the average value. The influent TP concentration is higher in September 2014 to January 2015 events (from 0.8 to 1.0 mg/L) and it can be explained by the decomposition of dead leaves (Brown et al. 2013; Davis et al. 2006), releasing nutrients. The event on April $14^{th}$ (the first rain event of the Spring) provided a very high TP level of 1.67 mg/L, and this may be the result of a long drought (> 2 weeks) from the winter, the leftover dead leaves, and the spread of pollen, a nutrition source (Brown et al. 2013; Shumilovskikh et al. 2015), during spring.

The cistern TP concentrations vary from 0.08 to 0.25 mg/L with the mean of 0.17 ± 0.04 mg/L. Other studies found an EMC median of 0.11 mg/L (Liu and Davis 2014), 0.15 and 0.17 mg/L (Davis 2007), 0.13 mg/L (Hunt et al. 2008), and 0.05 ± 0.02 mg/L (Passeport at al. 2009). Moreover, Hunt et al. (2006) found larger effluent TP concentrations of 0.56 ± 0.39 mg/L (from low-P index soil media) and 3.00 ± 3.4 mg/L (from high-P index soil media) than the influents from bioretentions in Greensboro, NC, showing possible leaching from the media. The cistern concentration is even less than 0.56 ± 0.39 mg/L from the case of low-P index soil media, indicating reasonable removal of the system comparing with previous studies. At 50% exceedance probability, the TP concentration is around 0.15 mg/L (Figure 3.3.2.1b).

The cistern TP (0.17 ± 0.04 mg/L) is less than the local tap water, 0.28 ± 0.015 mg/L in average (Table 3.3.2.1), because an extra source of phosphorus (phosphate) is injected into the water distributing system to coat the pipe for erosion prevention (Guan and Jin 2014). Phosphate also is used as microbe inhibitor (Danhorn et al. 2004; Herrera and Videla 2009). The TP level in the cistern is acceptable for irrigation as it is smaller than local tap water (0.28 ± 0.015 mg/L) and no TP criteria required by USEPA (2015).

The t-test (2 tails) shows that null hypothesis is rejected at the level of $p=0.05$. Besides, the Wilcoxon rank-sum test evaluation agreed with the 2-tail t-test at $\alpha = 5\%$. This means that the influent and cistern TSS concentrations are significantly different, showing good TP removal of the bioretention facility (Figure 3.3.2.1a).

The removal mechanisms of phosphorus (as phosphate) are plant uptake, filtration, and adsorption (LeFevre et al. 2014, Liu and Davis 2014). The amount of phosphorus uptake by plant is minimal; this process is mainly significant after rain events to remove retained phosphorus in bioretention media (Liu and Davis 2014). Filtration is an important removal mechanism of particulate phosphorus. As water runoff infiltrates through bioretention soil media, particulates that are larger than media pore size are retained within bioretention media.

Besides filtration, adsorption on the soil media's surface (e.g., cation exchange, specific adsorption, and chelation) is the main P-removal process of bioretention facilities. In this process, available $Al(OH)_3$, FeOOH and $Ca(OH)_2$ at the surface of soil particles allow dissolved phosphate ($PO_4$(-III)) to attach to the surface. Because of this process, the effluent concentration of phosphorus from a bioretention facility is often constant (Liu and Davis 2014). Randall and Bradford (2013) also found that phosphorus could be retained effectively in soil with high organic content. However, if the phosphorus concentration of soil media reaches its adsorption equilibrium, there will be a larger TP, compared to the inflow, exported from the system (Li and Davis 2009).

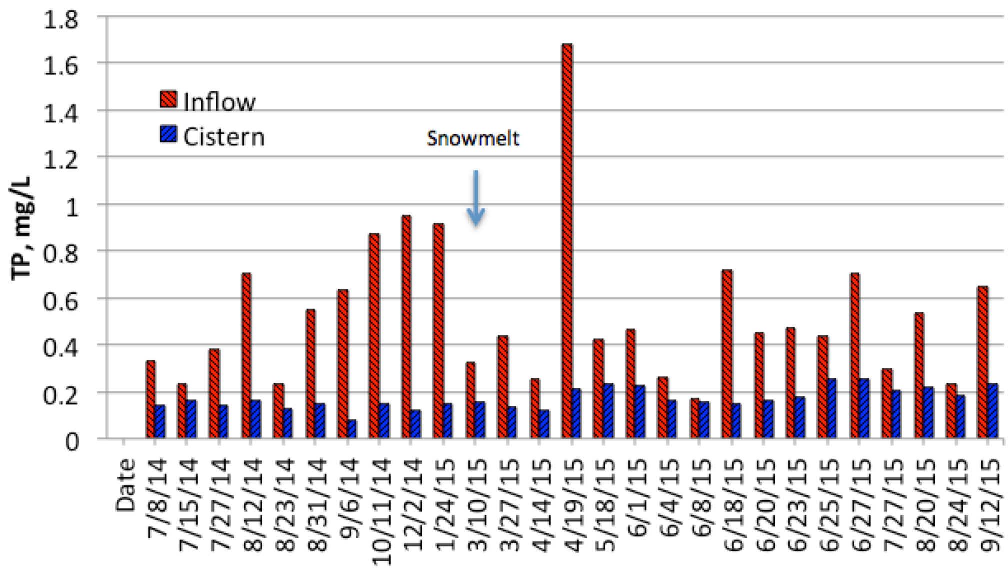



**Figure 3.3.2.1a**. TP concentration of 27 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

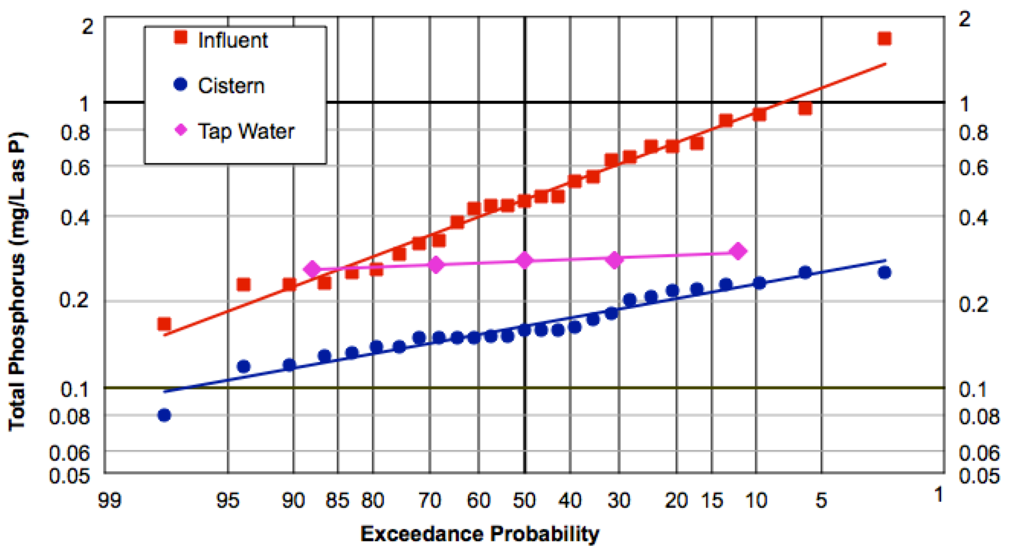



**Figure 3.3.2.1b.** Probability plot for total phosphorus concentration (27 samples) for the University of Maryland bioretention study.

**Table 3.3.2.1.** Total phosphorus concentrations for local tap water, cistern, and Potomac Water Filtration Plant for the University of Maryland bioretention study (n/d: not detected).

| Tap Water | TP, (mg/L) |
|---|---|
| 8/22/15 | 0.27 |
| 8/26/15 | 0.30 |
| 9/12/15 | 0.26 |
| 9/30/15 | 0.28 |
| 10/20/15 | 0.28 |
| Average Tap Water | 0.28 ± 0.02 |
| Potomac, 2014 | 0.29 (n/d – 0.33) |
| Average Cistern | 0.17 ± 0.04 |

*3.3.2.2 Phosphorus Speciation*

Water samples from the rain event on October 28th, 2015 were taken for phosphorus speciation analysis. The influent, cistern, and tap waters were analyzed for TP, dissolved phosphorus (DP) and phosphate (Ortho-P). The particulate phosphorus (PP) is the difference between TP and DP, and the dissolved organic phosphorus is the difference between DP and Ortho-P.

The influent sample on October 28th has 0.10 mg/L TP, 0.07 mg/L DP, 0.05 mg/L Ortho-P, 0.03 mg/L PP, and 0.02 mg/L DOP (Table 3.3.2.2). All values less than the detection limit are reported as < 0.01. Liu and Davis (2014) found EMC DP of 0.07 mg/L from a field study, which is similar to the result of this research. Influent Ortho-P concentrations found in other studies include 0.06 ± 0.07 mg/L (Passeport et al. 2009) and 0.05 ± 0.09 mg/L and 0.06 ± 0.06 respectively for Greenboro (G1) and G2 (Hunt et al. 2006). These values are larger than the result from this rain event, but not much different. The PP is much smaller than the DP because the TSS is only 80 mg/L. The

DOP is also small because Ortho-P is found to be the major P compound in stormwater runoff (Passeport et al. 2009).

The cistern water sample contains 0.07 mg/L TP, 0.08 mg/L DP, 0.08 mg/L Ortho-P, < 0.01 mg/L PP, and 0.01 mg/L DOP. These numbers are similar to 0.065 mg/L DP (Liu and Davis 2014), 0.01 and 0.01 mg/L Ortho-P (Passeport et al. 2009), and 0.52 ± 0.37 and 2.2 ±2.9 mg/L respectively for Greenboro G1 and G2 (Hunt et al. 2006), except for G2. Site G2 of Hunt et al. (2006) showed significant leaching of Ortho-P from the bioretention media.

Tap water has TP concentration larger than the cistern (as mentioned in the TP section) due to phosphate injection into water distribution system to inhibit pipe corrosion (Table 3.3.2.2). A major portion of TP is present as Ortho-P (0.20 mg/L out of 0.21 mg/L) with a little to no organic phosphorus in tap water. Table 3.3.2.2 indicates that orthophosphate is the major form of phosphorus in stormwater.

**Table 3.3.2.2.** Phosphorus speciation of a rain event on October 28, 2015, includes runoff (volume weighted composite), cistern and tap water for the University of Maryland bioretention study.

| 10/28/15 | TP (mg/L) | DP (mg/L) | Ortho-P (mg/L) | PP (mg/L) | DOP (mg/L) |
|---|---|---|---|---|---|
| Inflow | 0.10 | 0.07 | 0.05 | 0.03 | 0.02 |
| Cistern | 0.07 | 0.08 | 0.07 | < 0.01 | 0.01 |
| Tap water | 0.21 | 0.21 | 0.20 | < 0.01 | 0.01 |

### *3.3.3 Total Nitrogen/Nitrogen Speciation*

<u>*3.3.3.1 Total Nitrogen*</u>

Similar to TP, the influent TN concentrations range from 0.03 to 6.24 mg/L with the average of 2.23 ± 1.33 mg/L. The influent concentrations are high in the April 14th event (6.2 mg/L) when pollen was washed off from the drainage area (Figure 3.3.3a). For other seasons, the influent TN concentrations are less than 3 mg/L. At 50% probability, the influent concentration is about 2.00 mg/L (Figure 3.3.3b) Past studies found influent TN concentration of 5.73 ± 1.0 mg/L (Randall and Bradford 2013), 1.66 ± 0.97 mg/L (Passeport et al. 2009), EMC of 1.62 mg/L (Li and Davis 2014), EMC of 1.68 mg/L (Hunt et al. 2008) and 1.35 ± 0.70 mg/L and 1.27 ± 0.55 mg/L from bioretention facilities G1 and G2 respectively in Greensboro, NC (Hunt et al. 2006). These values are smaller than TN from this research (but not much), except for the results from Randall and Bradford (2013).

The cistern TN concentrations are generally less than 2 mg/L with many values less than 1 mg/L. They range from 0 to 2.38 mg/L with the mean of 1.08 ± 0.53 mg/L. The cistern concentrations are relatively less than effluent TN of 2.63 ± 0.67 mg/L from , 0.76 ± 0.33 and 0.76 ± 0.29 mg/L (Passeport et al. 2009), EMC of 1.55 mg/L (Li and Davis 2014), EMC of 1.14 mg/L (Hunt et al. 2008), and 4.38 ± 2.07 mg/L and 5.23 ± 3.42 mg/L from bioretentions in Greensboro, NC (Hunt et al. 2006). Effluent concentrations of TN from Hunt et al. (2006) are larger than the influent concentrations, showing significant leaching of TN from bioretention media (Hunt et al. 2006). The average cistern TN concentration (1.08 ± 0.53 mg/L) is significant less than effluent concentrations from Greensboro bioretention. The event on April 19th showed a good TN removal because the cistern value was around 1.2 mg/L while the influent value was high at 6.2 mg/L. The cistern TN concentration is around 1.00 mg/L at 50% probability provides which is slightly less than the average cistern concentration. Compared to the average of 1.84 ± 0.16 mg/L of TN in tap water and 1.6 mg/L (from 1.2-3.1 mg/L) from Potomac Water Filtration Plant, the cistern values are much less than tap water and water filtration plant. Besides, there are no criteria for the TN from USEPA (2012), except 10 mg/L $NO_3^-$-N and 1.0 mg/L $NO_2^-$-N for maximum contaminant level (MCL) for drinking water.

The probability plot of TN showed a similar trend between the influent and cistern data (Figure 3.3.3b). The space between the two lines is small, suggesting that the influent and cistern TN concentrations are different but the removal is not large. However, the t-test (2 tails) and the Wilcoxon Sign Rank Test show that null hypothesis is rejected at the level of p=0.05. It shows that the influent and cistern TN concentrations are significantly different, indicating possible TN removal of the bioretention facility.

The removal of nitrogen species includes sedimentation/filtration of particulate organic N, ion exchange of ammonium with bioretention media, nitrification (in oxic conditions) and denitrification (anoxic conditions) processes (Li and Davis 2014). For a bioretention facility, nitrification and denitrification generally occur after rain events because retention time may be long enough for microbial reactions. During rain events, sedimentation/filtration of particulate organic N and ion exchange of ammonium are likely to occur due to less retention time.

The first step of this removal is the ammonification of organic N to ammonium ($NH_4^+$) (LeFevre et al. 2014). The nitrification takes place to transform ammonium to nitrite and then nitrate with the present of oxygen and particular bacteria (Rittmann and

McCarty 2001). Denitrification process occurs with the present of facultative anaerobes (fungi) to break down nitrate to nitrite then to nitrogen gas (Chen et al. 2013; Kim et al. 2003).

Nitrification: Under oxic condition, $NH_3/NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$ (USEPA 2007)

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^- \text{ (Nitrosomonas) (Step 1)}$$

$$NO_2^- + H2O \rightarrow NO3^- + 2H^+ + 2e^- \text{ (Nitrobacter, Nitrospira) (Step 2)}$$

Denitrification: Under anoxic condition, $NO_3^- \rightarrow NO_2^- \rightarrow N_2$

$$6NO_3^- + 2CH_3OH \rightarrow 6NO_2^- + 2CO_2 + 4H_2O \text{ (Denitrifiers) (Step 1)}$$

$$6NO_2^- + 3CH_3OH \rightarrow 3N_2 + 3CO_2 + 3H_2O + 6OH^- \text{ (Denitrifier) (Step 2)}$$

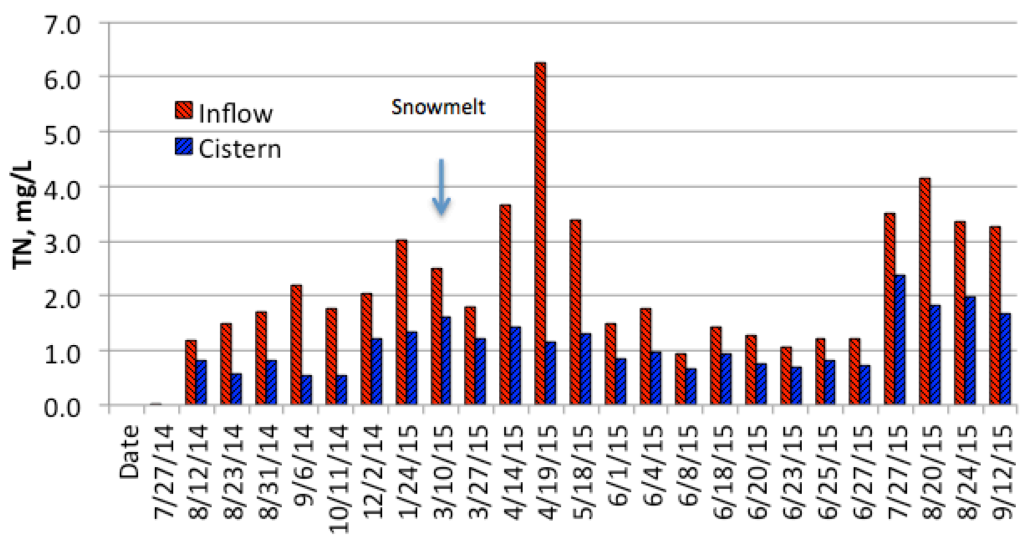



**Figure 3.3.3a**. TN concentration of 24 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

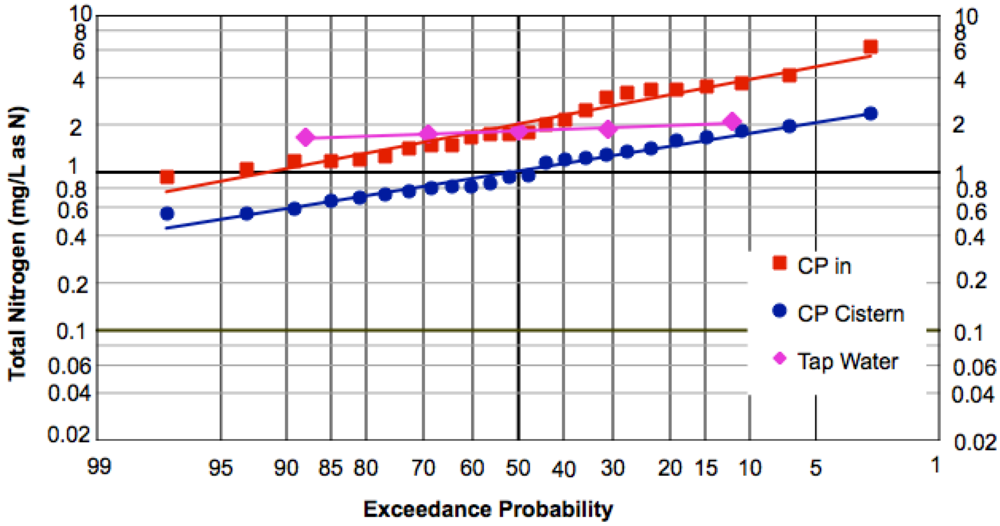



**Figure 3.3.3b.** Probability plot for total nitrogen concentration (24 samples) for the University of Maryland bioretention study.

**Table 3.3.3.1.** Total Nitrogen concentration for local tap water, cistern, and Potomac Water Filtration Plant for the University of Maryland bioretention study.

| Tap Water | TN, (mg/L) |
|---|---|
| 8/22/15 | 1.68 |
| 8/26/15 | 2.10 |
| 9/12/15 | 1.74 |
| 9/30/15 | 1.83 |
| 10/20/15 | 1.90 |
| Average Tap Water | 1.84 ± 0.16 |
| Potomac, 2014 | 1.60 (1.2 – 3.1) |
| Average Cistern | 1.08 ± 0.53 |

*3.3.3.2 Nitrogen Speciation*

Nitrogen speciation is presented in Table 3.3.3.2 (3 decimal places are used for comparison). The inflow of this rain event has 4.03 mg/L TN, 0.01 mg/L nitrite–N, 0.09 mg/L nitrate–N and 0.01 mg/L ammonium–N. The results show that nitrogen mainly exists as organic compounds. Nitrite–N and ammonium–N concentrations are very small, less than the detection limit of 0.01 mg/L. The influent concentrations are in reasonable range as compared to nitrite–N 0.02 mg/L and nitrate–N EMC 0.28 mg/L (Li and Davis 2014), Greenboro G1 nitrate–N of 0.34 ± 0.17 mg/L and G2 nitrate–N of 0.5 ± 0.32 mg/L (Hunt et al. 2006), ammonium–N of 0.15 mg/L (Li and Davis 2014) , $NO_{2,3}$-N 0.42 ± 0.23 mg/L and ammonium–N of 0.342 ± 0.28 mg/L (Passeport et al. 2009), and ammonium–N of 0.24 ±0.20 mg/L and 0.22 ± 0.18 mg/L respectively for G1 and G2 (Hunt et al. 2006). However, these past studies showed large concentrations of nitrate–N and ammonium–N in stormwater runoff.

The cistern water has 2.03 mg/L TN, < 0.01 mg/L nitrite–N, 0.53 mg/L nitrate–N, and < 0.01 mg/L ammonium–N. This indicates good TN removal of bioretention cells. The concentrations of nitrite–N and ammonium–N are close to 0, similar to the influent concentrations. However, nitrate–N concentration is much larger in cistern than inflow (0.53 vis-à-vis 0.09 mg/L). This indicates that some organic–N compounds were converted to nitrate–N in bioretention media. Other studies found nitrite–N < 0.01 mg/L, nitrate–N EMC 0.65 mg/L and ammonium–N < 0.05 mg/L (Li and Davis 2014); $NO_{2,3}$-N 0.28 ± 0.17 and 0.38 ± 0.19 mg/L and ammonium–N of 0.10 ± 0.10 and 0.06 ± 0.05 mg/L (Passeport et al. 2009); and G1 of 0.28 ± 0.43 mg/L nitrate–N, 2.82 ± 1.77 mg/L ammonium–N, G2 0.3 ± 0.42 nitrate–N and 1.54 ± 1.26 mg/L ammonium–N (Hunt et al. 2006). Cistern concentrations are consistent with other studies, except for large ammonium–N concentrations from Passeport et al. (2009) and Hunt et al. (2006).

Tap water has a larger TN concentration than the cistern water, but not much. There is little to no nitrite–N and ammonium–N in tap water, which is similar to cistern water. However, the nitrate–N concentration is larger, but not significant compared to total nitrogen, indicating majority fraction of organic–N.

**Table 3.3.3.2.** Nitrogen speciation of a rain event on October 28, 2015, and local tap water for the University of Maryland bioretention study.

| 10/28/15 | TN, (mg/L) | Nitrite–N, (mg/L) | Nitrate–N, (mg/L) | Ammonium–N, (mg/L) | Organic N, (mg/L) |
|---|---|---|---|---|---|
| Inflow | 4.03 | 0.01 | 0.09 | 0.01 | 3.92 |
| Cistern | 2.03 | < 0.01 | 0.53 | < 0.01 | 1.48 |
| Tap water | 2.27 | < 0.01 | 0.60 | < 0.01 | 1.65 |

### *3.3.4 Electrical Conductivity and pH*

#### *3.3.4.1 Electrical Conductivity*

Only 18 samples were sampled for the EC analysis. The values in the winter are significantly larger than other seasons (Figure 3.3.4.1). Snowmelts in March 2015 caused four events that have high EC in the cistern samples (from 0.5 to 4.5 mS/cm). The average influent EC is 0.51 ± 0.83 mS/cm. The influent samples have high EC during the winter season because salts (e.g., NaCl, $MgCl_2$ or $CaCl_2$), as deicing materials, are applied on the parking lot and road surfaces to increase the melting point of ice and snow (USEPA 1995). The influent and cistern EC values (from May to September 2015) are almost the same and significantly small compared to values of the winter season (much less than 0.5 mS/cm).

The average cistern EC is 0.44 ±1.02 mS/cm. The standard deviation is larger than the average value because deicing salt increased the EC in water samples from snowmelts and some rain events in early Spring season. For seasons not winter, the EC in the cistern (~0.11 mS/cm) is typically larger than inflow (~0.06 mS/cm) because there is not much salt in the inflow compared to the bioretention media and the existing salt in the cistern. The average cistern EC, excluding winter data, is approximately 0.11 ± 0.02 mS/cm (or dS/m), which is only about a half of the tap water (0.24 ± 0.01 mS/cm) and a quarter of

Potomac Water Filtration Plant 2014 (0.408 mS/cm); indicating that the cistern water is better than local tap water and Potomac Water Filtration Plant for irrigation in the term of EC.

The t-test (2 tails) shows that the null hypothesis is accepted at the level of p=0.05, meaning that the influent and cistern EC are not significantly different. However, the Wilcoxon Sign Rank Test indicates that the influent and cistern EC concentrations are significantly different, showing possible leaching of salt from the bioretention facility to the cistern. The Wilcoxon Sign Rank Test is selected because it is more reliable than t-test in this case. The salinity can be uptake by bioretention plants but high salinity may decrease bulb diameter, weight, height, root growth of plants, and number of leaves per plant (Shannon and Grieve 1999). Shannon and Grieve (1999) also found some salinity threshold where the productivity of plants starts decreasing, such as, 1.4 mS/cm for onion, 3.9 mS/cm for garlic, 4.1 mS/cm for asparagus, 1 mS/cm for carrot, 1.3 mS/cm for lettuce, and 2.0 mS/cm for spinach. These values are larger than the cistern water (excluding winter season) and tap water. Moreover, the cistern and tap water EC concentrations are less than Class 1 of irrigation water of 0.270 mS/cm (~175 mg/L Na) (Table 3.3.4.2). Thus, cistern water from other seasons and tap water is acceptable for irrigation of most crops on most soils in term of salinity.

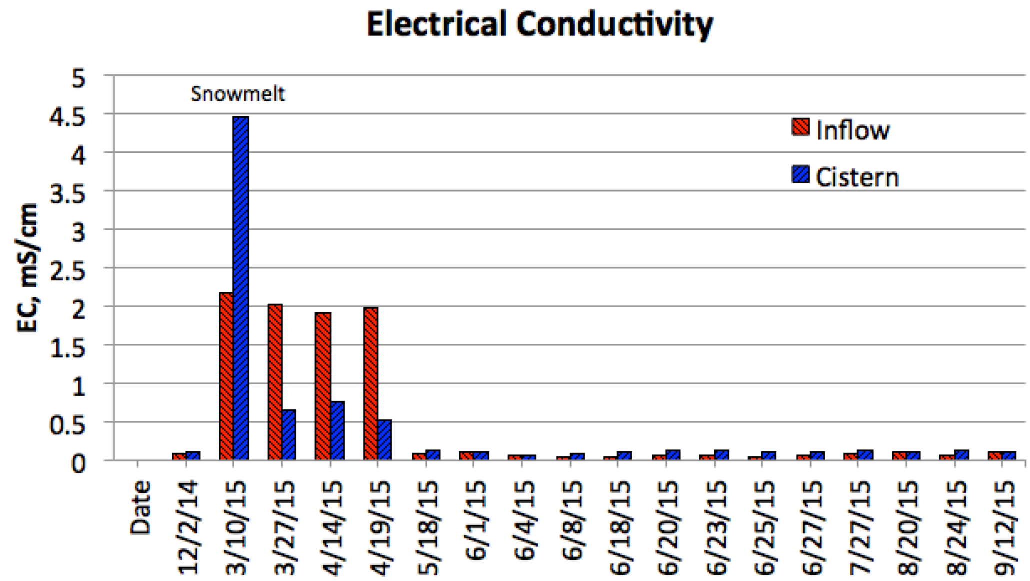



**Figure 3.3.4.1**. Electrical conductance of 18 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

*3.3.4.2 pH*

The results showed that the bioretention provides some effects on the pH. The influent pH has the average of 7.25 ± 0.42 (ranging from 6.21 to 7.70). This value is in the allowable range of pH 6.5 to 8.5 for drinking water standards (USEPA 2012). The pH in the cistern ranges from 5.86 to 7.54 with the average of 6.98 ± 0.49. Similar to the influent pH, the cistern average value is within the allowable range (6.5 to 8.5) for drinking water standards (USEPA 2012). The pH values are significantly different between the influent and cistern, but they are near neutral pH, ranging from 5.8 to 7.7. The pH in the cistern appears to be less than values from the inflow due to the neutralizing capacity of bioretention media ($Ca^{2+}$, $Mg^{2+}$, and $K^{+}$ ions), indicating why the bioretention has some effects on the pH. Moreover, the t-test (2 tails) and the Wilcoxon Sign Rank Test show that null hypothesis is rejected at the level of p=5 %, and that the influent and cistern pH concentrations are significantly different. Randall and Bradford (2013) showed that the influent and effluent pH of the bioretention facility in their study remained near the neutral pH of 7. Compared to UMD tap water and data from Potomac Water Filtration Plant 2014, the averages in pH are 7.14 ± 0.13 and 7.4 respectively, indicating that the cistern water is in the allowable range for irrigation (USEPA 2012 & 2015).

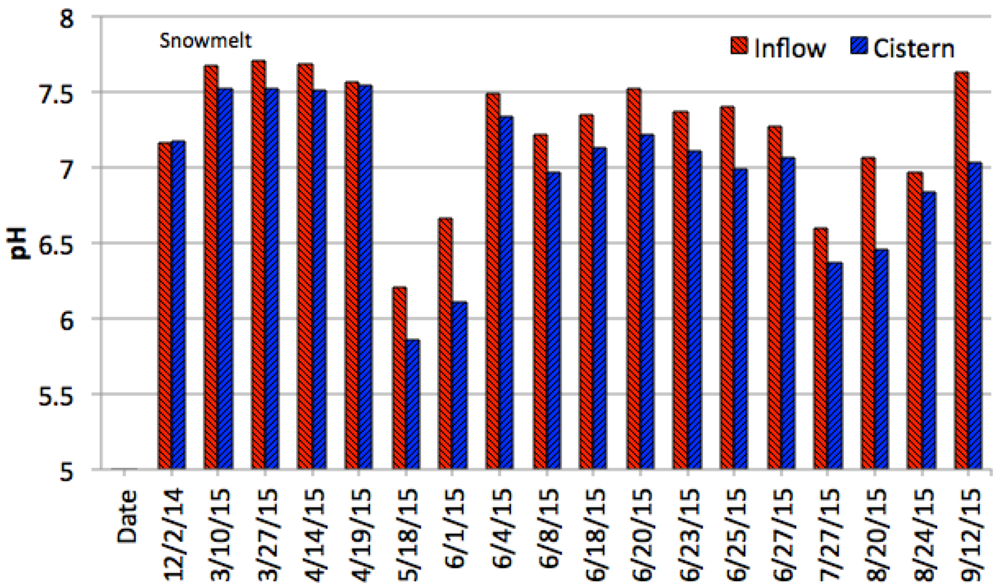



**Figure 3.3.4.2**. The pH of 18 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

**Table 3.3.4.1.** Total phosphorus concentration for local tap water, cistern, and Potomac Water Filtration Plant for the University of Maryland bioretention study.

| Tap Water | EC, (mS/cm) | pH |
|---|---|---|
| 8/22/15 | 0.245 | 7.13 |
| 8/26/15 | 0.227 | 7.27 |
| 9/12/15 | 0.256 | 7.21 |
| 9/30/15 | 0.248 | 6.94 |
| 10/20/15 | 0.223 | 7.16 |
| Average Tap Water | 0.24 ± 0.01 | 7.14 ± 0.13 |
| Potomac, 2014 | 0.408 (0.240 – 0.847) | 7.4 (7.1 – 7.7) |

| | | |
|---|---|---|
| Average Cistern | 0.11 ± 0.02 | 6.98 ± 0.49 |

**Table 3.3.4.2.** Salinity classes of irrigation waters (Australian Environment Protection Authority 1991).

| Class | TDS* ($mg \cdot L^{-1}$) | EC* ($\mu S \cdot cm^{-1}$) | Comments |
|---|---|---|---|
| 1 | 0–175 | 0–270 | Can be used for most crops on most soils by all methods or water application with little likelihood that a salinity problem will develop. Some leaching is required, but this will occur under normal irrigation practices, except in soils of extremely low soil permeabilities. |
| 2 | 175–500 | 270–780 | Can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown, usually without special salinity management practices. Sprinkler irrigation with the more saline waters in this class may cause leaf scorch on salt-sensitive crops. |
| 3 | 500–1500 | 780–2340 | Do not use the more saline waters in this class on soils with restricted drainage. Even with adequate drainage, best practice management controls for salinity may be required, and the salt tolerance of the plants to be irrigated must be considered. |
| 4 | 1500–3500 | 2340–5470 | For use, soils must be permeable with adequate drainage. Water must be applied in excess to provide considerable leaching, and salt-tolerant crops should be grown. |
| 5 | >3500 | >5470 | Not suitable for irrigation except on well drained soils under good management, especially leaching. Restrict to salt-tolerant crops, or for occasional emergency use. |

## 3.4 Heavy Metals

### *3.4.1 Copper*

The results indicate average influent Cu concentrations of 19.3 ± 14.7 μg/L (from 7.2 to 72.2 μg/L). Other studies found EMC 10 μg/L (Davis 2007), 12.8 μg/L (Hunt et al. 2008), 19 and 13 μg/L respectively for College Park and Silver Spring bioretention cells (Li and Davis 2009), and 66 ± 32 μg/L Greenbelt field study and 120 ± 27 μg/L Largo field study (Davis et al. 2003), that cover the range of this research influent copper concentrations. At 50% probability, the influent copper concentration is approximately 15 μg/L, which is typically small compared to past studies. Concentrations from March to April are higher than other times of the year because the accumulation times between these events are longer than 2 weeks.

The average of cistern concentration is15.7 ± 17.6 μg/L (from 2.7 to 81.6 μg/L). At 50 % probability, the cistern concentration is 10 μg/L. Comparing to effluent concentrations of 4 and 3 μg/L (Davis 2007), 5.9 μg/L (Hunt et al. 2008), 16 and 9 μg/L respectively for College Park and Silver Spring bioretention cells (Li and Davis 2009), and 2 ± 1 μg/L Greenbelt field study and 69 ± 9.4 μg/L Largo field study (Davis et al. 2003), the cistern values are smaller than the Largo study but much more than other studies. The cistern concentrations before December 2014 are mostly larger than the in flow from May 2015 because after the pump was installed, the treated water in the cistern was frequently recirculated back to the bioretention system for further treatment or to the rain barrels for irrigation.

The effluent copper concentrations from past studies and this study are still lower than 168 ± 6.1 μg/L (with n = 5) of local tap water because copper pipes are generally used in the water distributing system and it is the reason of having high Cu concentration in tap water (Clark et al. 2015; Deshommes et al. 2010; Knowles et al. 2015). The copper concentration reported from Potomac Water Filtration Plant 2014 also shows copper contamination in water distributing system. The cistern copper concentration is typically less than the value for LC50 for the most freshwater animals (e.g. 8-2000 μg/L for snails, 33-199 μg/L for salmon, and 1000-1100 μg/L for bluegill), 1,000 μg/L (USEPA 2012) and 1,300 μg/L for human (EPA 2007), but it is higher than 12 μg/L (acute) and 9 μg/L (chronic) for aquatic life in freshwater; thus, it is safe, in the term of copper, for irrigation but not downstream aquatic environment.

The Cu(II) probability plot for the inflow values has a mild slope comparing to the cistern, indicating that the Cu values vary less than the cistern (Figure 3.4.1.1b). The t-test (2 tails) shows that the null hypothesis is accepted at the level of $p = 0.05$, meaning that the influent and cistern Cu are not significantly different. However, The Wilcoxon Sign Rank Test indicates that they are significantly different, showing possible significant removal of the bioretention facility. This discrepancy is caused by lower influent Cu concentrations before June 1$^{st}$ 2015. There is Cu removal in later events; thus, the Wilcoxon sign rank test takes over the t-test (2 tails).

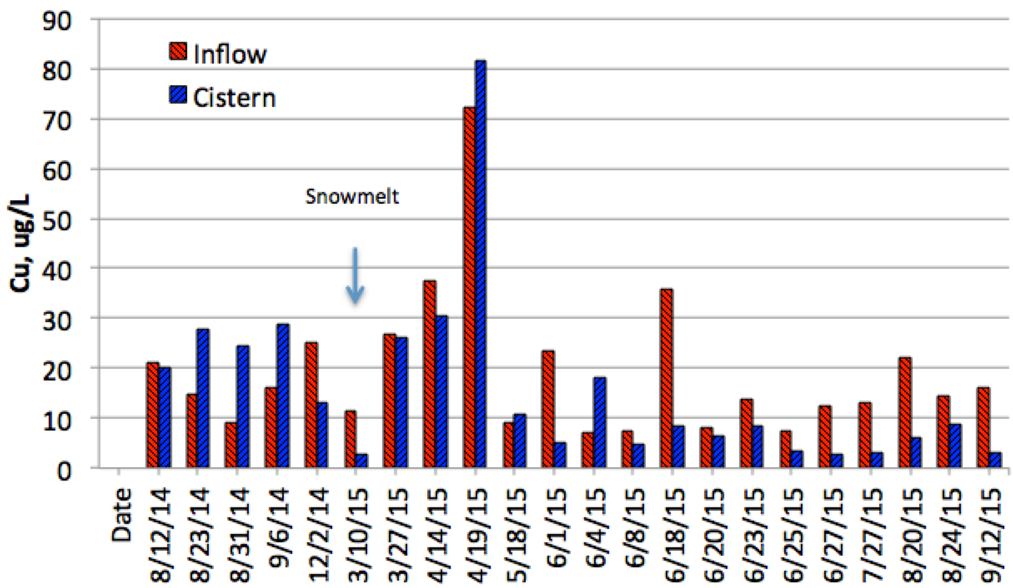



**Figure 3.4.1.1a**. Copper concentration of 22 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

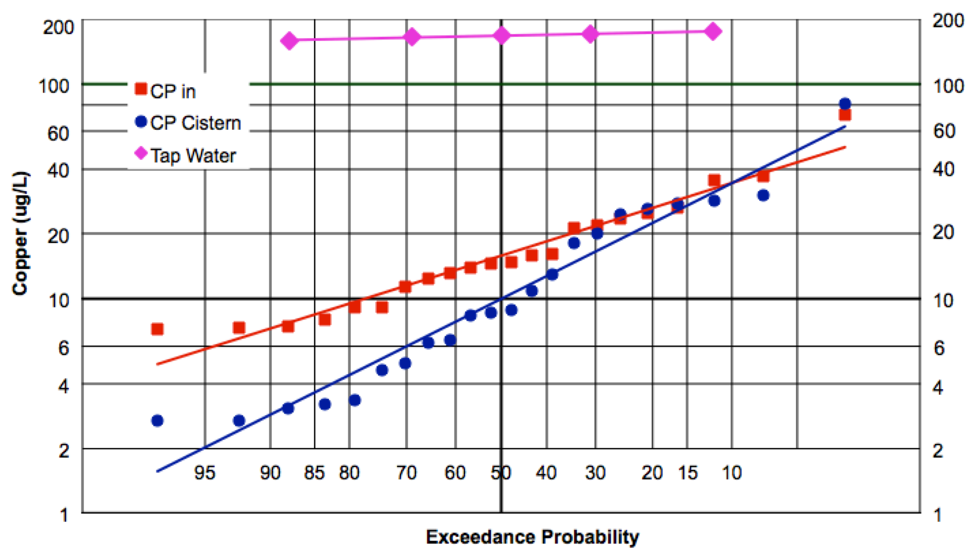



**Figure 3.4.1.1b**. Probability plot for copper concentration (22 samples) for the University of Maryland bioretention study.

**Table 3.4.1.1.** Copper concentrations for local tap water, cistern, and Potomac Water Filtration Plant for the University of Maryland bioretention study.

| Tap Water | Cu, (µg/L) |
|---|---|
| 8/22/15 | 159 |
| 8/26/15 | 172 |
| 9/12/15 | 166 |
| 9/30/15 | 169 |
| 10/20/15 | 175 |
| Average Tap Water | 168 ± 6.1 |
| Potomac, 2014 | < 2<br>(< 2 – 8) |
| Average Cistern | 15.7 ± 17.6 |

### *3.4.2 Lead*

Influent lead concentration, 5.3 ± 3.1 µg/L (from 1.9 to 15.4 µg/L), is smaller than 58 µg/L (Davis 2007), 4.9 µg/L (Hunt et al. 2008), 6 and < 2 µg/L respectively for College Park and Silver Spring bioretention cells (Li and Davis 2009), 42 ± 35 µg/L of the Greenbelt field study and 54 ± 9.4 µg/L of the Largo field study (Davis et al. 2003), except for the Silver Spring MD bioretention cell. Davis (2007) and Davis et al. (2003) studies showed large lead concentrations for the inflows. The influent concentration is 5 µg/L at 50% probability (Figure 3.4.2.1). Inflow concentrations from June 1$^{st}$ 2015 are much larger than the cistern, except the value on August 20$^{th}$; indicating good removal by the system.

Cistern lead concentrations, mean of 0.87 ± 1.3 µg/L (from 0.13 to 5.07 µg/L) and 0.55 µg/L at 50% probability, are less than < 2 and 4 µg/L (Davis 2007), 3.33 µg/L (Hunt et al. 2008), 3 and < 2 µg/L respectively for College Park and Silver Spring MD bioretention cells (Li and Davis 2009), < 2 µg/L of the Greenbelt field study and 16 ± 7 µg/L of the Largo field study (Davis et al. 2003). The variation for the cistern values is larger than its average; this is due to having a high concentration of 5.1 μg/L on August 20th 2015. Moreover, the influent Pb concentration is much larger (~ 6 times) than cistern concentration; indicates good removal by bioretention cells.

The average cistern concentration is similar to the tap water concentration of 0.9 ± 0.48 μg/L, indicating that they both provide the same amount of lead to the vegetable garden. From Potomac Water Filtration Plant, lead concentration was not detected (n/d) (Table 3.4.2.1) but increased significantly (higher in local tap water) from water distribution system and the reason of this is the use of Galvanized steel pipe (Clark et al. 2015) and lead-based solder (Deshommes et al. 2010; Knowles et al. 2015). They are the reasons of lead accumulation in tap water. The cistern lead concentration is typically less than the value for 65 μg/L (acute) and 2.5 μg/L (chronic) for MD freshwater animals and a Maximum Contaminant Level (MCL) of 15 μg/L for human from MD Drinking Water (MDEPA 2007); thus, it is acceptable to directly release cistern water into the stormwater system.

The probability plots for the inflow and the cistern have similar slopes, indicating similar variation but different magnitude (Figure 3.4.2.1b). Moreover, the t-test (2 tails) and the Wilcoxon Sign Rank Test show that null hypothesis is rejected at the level of $p=0.05$, indicating significant difference between influent and cistern lead concentrations.

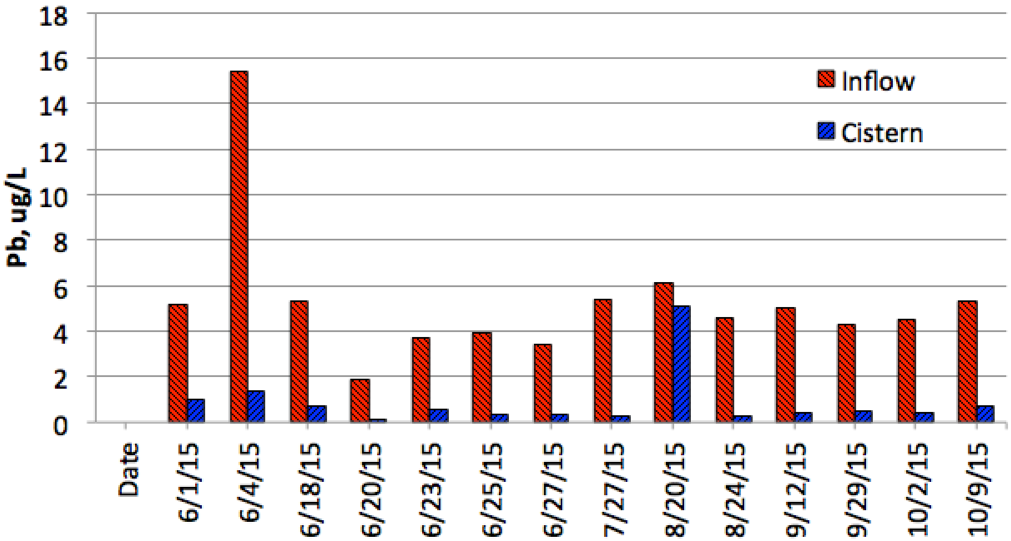



**Figure 3.4.2.1a**. Lead concentration of 14 water samples (March 10, 2015) for the University of Maryland bioretention study.

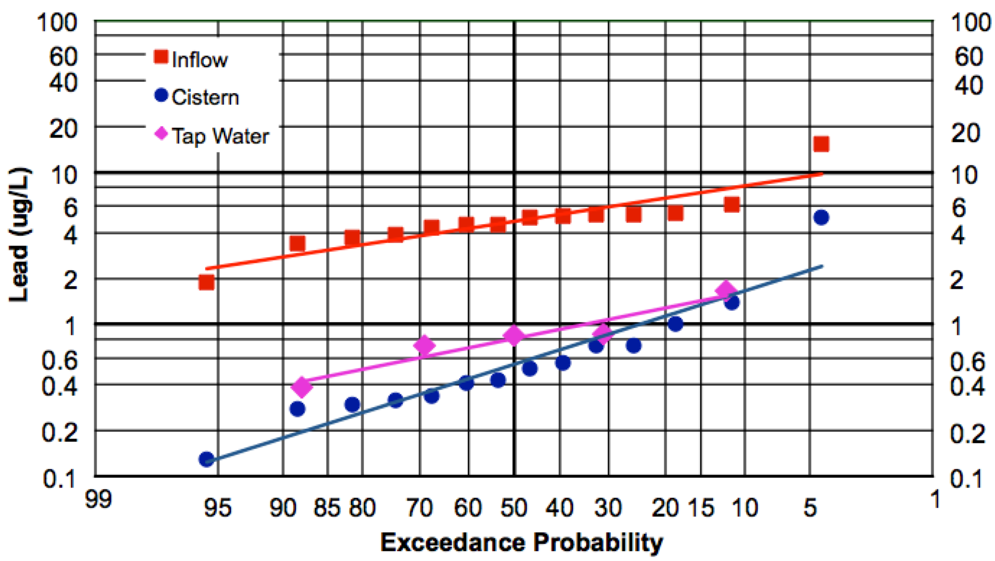



**Figure 3.4.2.1b**. Probability plot for lead concentration (14 samples) for the University of Maryland bioretention study.

**Table 3.4.2.1.** Lead concentrations for local tap water, cistern, and Potomac Water Filtration Plant for the University of Maryland bioretention study. (n/d: not detected)

| Tap Water | Pb, (μg/L) |
|---|---|
| 8/22/15 | 1.68 |
| 8/26/15 | 0.39 |
| 9/12/15 | 0.72 |
| 9/30/15 | 0.85 |
| 10/20/15 | 0.86 |
| Average Tap Water | 0.90 ± 0.48 |
| Potomac, 2014 | n/d |
| Average Cistern | 0.87 ± 1.3 |

### *3.4.3 Zinc*

Zinc concentrations are larger in the inflow with the average of 58 ± 56.2 μg/L. Compared to other field studies that have influent concentration of 107 μg/ (Davis 2007), 72 μg/L (Hunt et al. 2008), 530 ± 72 and 1100 ± 20 μg/L respectively for the Greenbelt and Largo field studies (Davis et al. 2003), and 71 and 15 μg/L respectively for College Park and Silver Spring MD bioretention facilities (Li and Davis 2009), the influent concentration is typically smaller except for result from Silver Spring bioretention facility (Li and Davis 2009). Zinc concentration in the inflow was estimated to be 38 μg/L at 50% probability, which is also less than the influent average concentration. The inflow concentration on June 1$^{st}$ 2015 is significantly larger than the snowmelt on March and other times; this could be the reason of having a long drought period (typically longer than 2 weeks). For recent data (after June 1$^{st}$), the result shows that the inflow samples have much higher concentration than the cistern and the cistern values do not vary significantly (~ 18 μg/L), indicating a good removal of Zn by the bioretention facility.

The cistern concentrations, that were estimated to be 12.2 ± 6.3 μg/L, are lower than 48 and 44 μg/L (Davis 2007), 17 μg/L (Hunt et al. 2008), < 25 μg/L and 390 ± 440 μg/L respectively for the Greenbelt and Largo field studies (Davis et al. 2003), and 12 and 3 μg/L respectively for College Park and Silver Spring MD bioretention cells (Li and Davis 2009) except for the study of the Silver Spring MD bioretention cell. It is reasonable because the influent zinc concentration of Silver Spring study is also less than the concentration of this study, showing a similar removal trend for two systems. Moreover, The Greenbelt study showed a very good removal of zinc and its effluent concentration is still lower than 88 ± 44.6 μg/L of local tap water (n = 5). The Trowsdale and Simcock (2011) found a good zinc removal from the research, 659 μg/L and 29 μg/L for influent and effluent respectively. The effluent concentration is twice as large as the cistern but these values are still less than local tap water.

Compared to data from Potomac Water Filtration Plant, zinc concentration increases significantly during water distribution (from less than 2 to 88 μg/L) and the reason for this is the use of Galvanized steel pipe that contains a zinc-coating layer (Clark et al. 2015). The cistern zinc concentration is typically less than the value for 130 μg/L of both acute and chronic effects (correspond to a hardness of 100mg/L) freshwater animals, 7,400 μg/L for human (EPA 2007) and 5,000 μg/L for Secondary Drinking Water Regulation (USEPA 2012); thus, it is reasonable to directly release cistern water into the stormwater system in term of zinc.

The probability plot for the inflow values has a steeper slope comparing to the cistern, indicating that the Zn values vary significantly (at different magnitude) in the inflow than the cistern (Figure 3.4.3.1b). The t-test (2 tails) and the Wilcoxon Sign Rank Test show similar decision for zinc. The null hypothesis is rejected at the level of $p = 0.05$; thus, the influent and cistern zinc concentrations are significantly different, indicating significant zinc removal of bioretention.

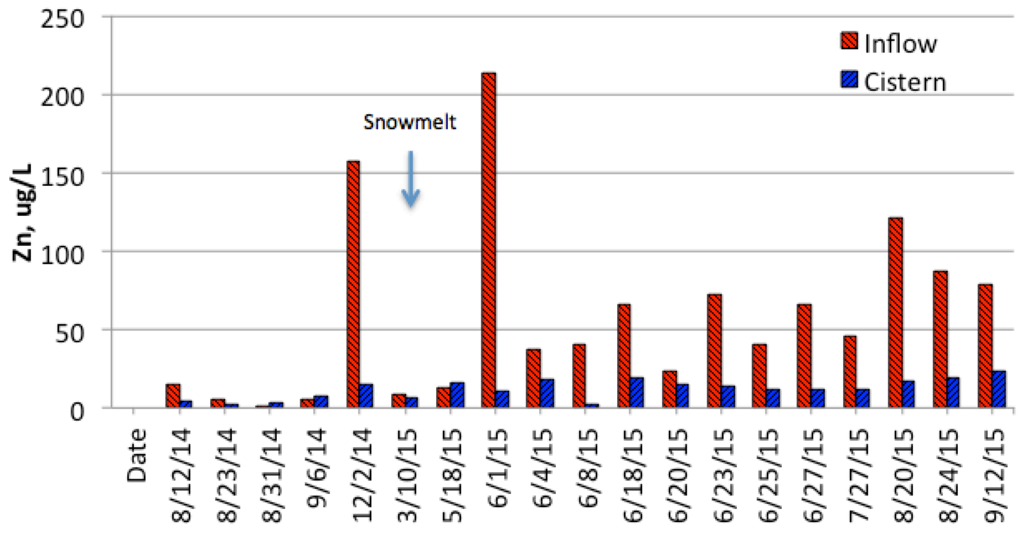



**Figure 3.4.3.1a**. Zinc concentration of 19 water samples including 1 snowmelt sample (March 10, 2015) for the University of Maryland bioretention study.

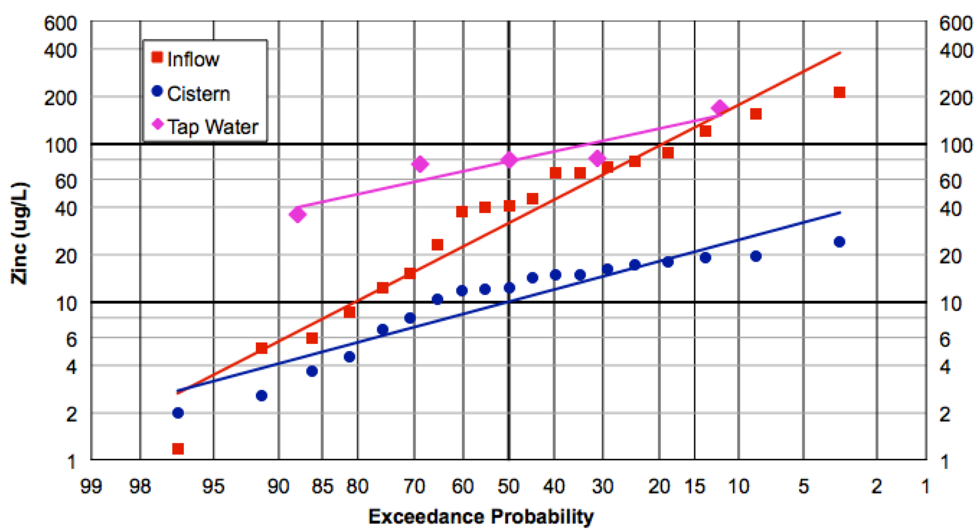



**Figure 3.4.3.1b**. Probability plot for zinc concentration (19 samples) for the University of Maryland bioretention study.

**Table 3.4.3.1.** Zinc concentrations for local tap water, cistern, and Potomac Water Filtration Plant for the University of Maryland bioretention study.

| Tap Water | Zn, (μg/L) |
|---|---|
| 8/22/15 | 168 |
| 8/26/15 | 36 |
| 9/12/15 | 81 |
| 9/30/15 | 74 |
| 10/20/15 | 79 |
| Average Tap Water | 88 ± 44.6 |
| Potomac, 2014 | 2 (< 2 – 3) |
| Average Cistern | 12.2 ± 6.3 |

The removal mechanisms for heavy metals (Cu, Pb, and Zn) is adsorption on the soil media (e.g., cation exchange, specific adsorption, and chelation) (Li and Davis 2008) and the uptake by plants (LeFevre et al. 2014). Because plant uptake only accounts for a small fraction of heavy metals uptake, especially during storm events, adsorption is the main removal mechanism (Hunt et al. 2006; Liu and Davis 2014). As heavy metals ions have positive charges, they will adsorb to available sites of the surface of soil particles (negative charges). However, copper has a weaker association with soil media than lead and zinc; therefore, it has a tendency to stick with dissolved organic matter and leach out of the media (Li and Davis 2008).

### 3.5 Irrigation

The solar pump was installed in November 2014, but was not used until May 2015. Due to higher-than-usual rainfall, from June 2015 through November 2015, there were only two times that the treated water in the cistern was pumped to the vegetable garden for irrigation. For other times, the cistern water was released to the stormwater system because of several reasons 1) the cistern contained high EC water right after the winter season, 2) the rain barrels were not ready to store treated water, and 3) the cistern needed to be emptied for the coming rain event. Each time, the cistern water was pumped to the vegetable garden; approximately 1,325 L was pumped to store in rain barrels for future irrigation.

Table 3.5.1 provides information on how much treated water was used for irrigation and the pollutant loads on the garden. Also, this table provides the pollutant loads if tap water instead of cistern water is used for irrigation. Based on the concentrations of cistern water and tap water, the pollutant loads were estimated. The load is the product of irrigation water volume with the corresponding concentrations of that time period (C x V). Table 3.5.1 also shows Load Gained = (Tap – Cistern)/Cistern x 100. The result showed that the treated water provides much less TP, TN, Cu, and Zn, but not much in Pb. For example, if tap water is used for irrigation, the amount of copper entering the garden is 49.5 times larger than the Cu load from cistern water.

**Table 3.5.1:** Water volume and pollutant loads (TP, TN, Cu, Pb and Zn) through irrigation onto The Public Health Garden, the University of Maryland bioretention study.

| Period | Irrigation V, L | TP Load, (g) | | TN Load, (g) | | Cu Load, (g) | | Pb Load, (g) | | Zn Load, (g) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cistern | Tap Water | Cistern | Tap Water | Cistern | Tap Water | Cistern | Tap Water | Cistern | Tap Water |
| 7/27/15 | 1283 | 0.30 | 0.34 | 0.78 | 2.15 | 4.11E-03 | 2.04E-01 | 2.69E-03 | 2.18E-03 | 1.51E-02 | 2.16E-01 |
| 10/2/15 | 1325 | 0.30 | 0.37 | 1.78 | 2.42 | 4.37E-03 | 2.24E-01 | 5.70E-04 | 1.13E-03 | 2.98E-02 | 9.74E-02 |
| Total | 2608 | 0.61 | 0.71 | 2.56 | 4.58 | 8.48E-03 | 4.28E-01 | 3.26E-03 | 3.31E-03 | 4.50E-02 | 3.13E-01 |
| Load Gained, % | | | 16.8 | | 78.9 | | 4950 | | 1.3 | | 596 |

The 2012 *Guidelines for Water Reuse* (USEPA, 2012) show that treated wastewater and stormwater are reused for many purposes, such as: 18% for urban reuse (landscape, golf courses and recreational field irrigation), 29% for agricultural reuse, 4% for environmental reuse (wetland, river or stream flow augmentation, ecological impacts of environmental reuse), 14% for industrial reuse (cooling towers and boiler water makeup), 5% ground water recharge (nonpotable), < 1% for potable reuse, and 29% other. The water quality for agricultural and livestock drinking reuse water is addressed in Table 3.5.2 (USEPA 2012). "Non restriction" means that water quality less than these values are good for reuse without causing any harm, except for the pH. The pH value is recommended to be from 6.5 to 8.5 (neutral range).

**Table 3.5.2:** Guidelines for water reuse for agricultural and livestock drinking purposes (USEPA 2012) (N/A = Not Applicable).

| | Agricultural Reuse | Livestock Reuse | Cistern Water |
|---|---|---|---|
| Parameters | Non restriction | Non restriction | |
| EC, mS/cm | < 0.7 | N/A | 0.11 ± 0.02 |
| pH | 6.5 - 8.5 | N/A | 6.98 ± 0.49 |
| TDS, mg/L | < 450 | N/A | N/A |
| TSS, mg/L | N/A | N/A | 14 ± 10.3 |
| TN, mg/L | N/A | N/A | 1.08 ± 0.53 |
| Nitrate–N, mg/L | < 5 | < 10 | 0.53 |
| Nitrate–N + Nitrite–N, mg/L | N/A | < 100 | 0.54 |
| Cu, ug/L | < 200 | < 500 | 15.7 ± 17.6 |
| Pb, ug/L | < 5,000 | < 100 | 0.87 ± 1.3 |
| Zn, ug/L | < 2,000 | < 24,000 | 12.2 ± 6.3 |

The result from this study showed that the cistern water quality values are much less than criteria indicated in Table 3.5.2 from USEPA (2012), especially heavy metals Cu, Pb and Zn. TN values are not addressed in Table 3.5.2; however, TN from this research is significantly less than values for nitrate–N (< 5 mg/L) for agricultural reuse, nitrite–N (<

10 mg/L) and nitrate–N + nitrite–N (< 100 mg/L) for livestock drinking reuse. Similar to TN, TP is not provided in The 2012 Guideline for Water Reuse; however, data from this research showed that the average TP from the cistern is less than local tap water (0.28 ± 0.02 mg/L). For agricultural purposes, higher values of TN and TP are acceptable because these constituents are nutrients for plants.

The Maryland Department of Environment published guidelines for land application/reuse of treated municipal wastewaters (MDE 2010). Table 3.5.3 shows criteria on Biological Oxygen Demand ($BOD_5$), TSS, fecal coliform, and the required pH for the treated wastewater. These treated wastewaters are classified as Class I, Class II, and Class III (highly treated). Class III effluent can be used in non-restricted public access areas such as, parks, playgrounds, school yards, cemeteries, highway landscaping and other green open spaces. The treated wastewater is applied on land surface by spray irrigation (slow rate), overland flow, and rapid infiltration (MDE 2010). The BOD, TSS, bacterial and viral organisms, and other nutrients are greatly reduced as the treated water infiltrates and percolates through soil profile to recharge groundwater system. The nutrients removed by the soil are available for plant takeup. The irrigation is used in this project with the cistern has a TSS concentration of 14 ± 10.3 mg/L, meeting Class I requirements. Also, the pH from 6.5 to 8.5 is acceptable. However, the BOD and the fecal coliform need to be measured to classify the treated stormwater.

**Table 3.5.3:** Minimum Pre-Application Treatment Requirements for Various Land Application Systems[a], Guidelines for Land Application/Reuse of Treated Municipal Wastewaters (MDE 2010).

| Parameter | Slow Rate | | | Overland Flow | Rapid Infiltration |
|---|---|---|---|---|---|
| | Class I | Class II | Class III | | |
| 5 day - Biochemical Oxygen Demand (monthly average) | 70 mg/l | 10 mg/l | 10 mg/l | 70 mg/l | Case by case |
| Suspended Solids (monthly average) or Turbidity (NTU) (continuous monitoring) | 90 mg/l | 10 mg/l | 2 NTU (daily average)<br>Not to exceed 5 NTU at any time | 90 mg/l | Case by case |
| Fecal Coliform [a] (MPN per 100 mL; monthly geometric mean) | 200<br>3 (golf courses) | 3 | 2.2 | 200 | Case by case |
| pH | 6.5 - 8.5 | 6.5-8.5 | 6.5-8.5 | 6.5 - 8.5 | 6.5-8.5 |

a Higher levels of treatment and disinfection may be required under certain conditions such as a land application site located in a well head protection area with a significant amount of rocks fragments in the soil.

# CHAPTER 4. CONCLUSION & RECOMMENDATIONS

In general, the research site was well constructed to successfully collect and treat stormwater runoff and store it for irrigation purpose. However, the site still needs some improvements to closely approach zero-discharge and irrigation purposes. The results of this project showed that:

- The drainage area of this research was estimated to be 2,604 ± 448 $m^2$, approximately 40%, on average, larger than the original drainage area of 1858 $m^2$.
- Zero discharge from the site is not feasible because of the undersized bioretention facility (22.44 $m^2$/2604 $m^2$ = 0.86%) based on the estimated drainage area of 2,604 $m^2$). Large rainfall intensity will cause overflow at the final cell (rainfall of greater than 0.75 cm in 2 hours). Moreover, if the rain duration is too short (e.g. < 1 hour), a rainfall of less than 0.75 cm may still cause overflow at the bioretention $3^{rd}$ cell.
- It is feasible to use bioretention-treated water for irrigation. Water qualities for inflow and cistern are reasonable for storm water runoff treated by a standard bioretention system. The cistern has average values of 14 ± 10.3 mg/L TSS, 0.17 ± 0.04 mg/L TP, 1.08 ± 0.53 mg/L TN, 15.7 ± 17.6 μg/L Cu, 0.87 ± 1.3 μg/L Pb, 12.2 ± 6.3 μg/L Zn, 0.11 ± 0.02 mS/cm EC, and 6.98 ± 0.49 pH. (Table 4) These values are much less than local tap water (0.28 ± 0.02 mg/L TP, 1.84 ± 0.16 mg/L TN, 168 ± 6.1 μg/L Cu, 0.90 ± 0.48 μg/L Pb, 88 ± 49 μg/L Zn, 0.24 ± 0.1 mS/cm EC, and 7.14 ± 1.3 pH), except for Pb. The EC is half of the tap water with neutral pH ranging between 6 and 8. Comparing to tap water and Drinking Water

Standards and Health Advisories from USEPA, the cistern water should be acceptable for irrigation.

- **Table 4:** Summarized table for water qualities of the University of Maryland bioretention study.

| Water Parameters | Inflow | Cistern | Tap Water |
|---|---|---|---|
| **TSS, mg/L** | 164 ± 104 | 14 ± 10.3 | n/d |
| **TP, mg/L** | 0.53 ± 0.32 | 0.17 ± 0.04 | 0.28 ± 0.02 |
| **TN, mg/L** | 2.23 ± 1.33 | 1.08 ± 0.53 | 1.84 ± 0.16 |
| **Cu, µg/L** | 19.3 ± 14.7 | 15.7 ± 17.6 | 168 ± 6.1 |
| **Pb, µg/L** | 5.3 ± 3.1 | 0.87 ± 1.3 | 0.90 ± 0.48 |
| **Zn, µg/L** | 58 ± 56.2 | 12.2 ± 6.3 | 88 ± 44.6 |
| **EC, mS/cm** | 0.51 ± 0.83 | 0.11 ± 0.02 | 0.24 ± 0.01 |
| **pH** | 7.25 ± 0.42 | 6.98 ± 0.49 | 7.14 ± 0.13 |

- The installation of solar panel is effective to provide clean energy for circulating water within the system. An amount of 2.6 $m^3$ of treated stormwater was successfully used for irrigation.

Some recommendations for further researches are:

1. The overflow cage and the berm of the 3rd cell should be raised to a higher level to allow more runoff to percolate through bioretention media (higher water potential pressure) and to reduce the chance of overflow. Moreover, a new soil media with a higher hydraulic conductivity could be used to replace the current bioretention media to allow more filtration. These options may reduce pollutant removal of bioretention due to less retention time in bioretention media. The pollutant concentration in the effluent will be higher than current result but may still be safe for irrigation purposes.
2. Several berms should be constructed at the end of other bioretention cells to provide bowl volume. Having these berms will allow more water filtration at these cells and reduce the pressure for overflow in bioretention cell 3.

**3.** An extra cistern/chamber can be installed underground to temporarily store overflow volume during rain events. After rain events, the water inside this chamber will be pumped back to the bioretention facility for treatment. This will help to limit the deterioration of downstream water body, to retain more stormwater runoff for irrigation, and to provide better pollutant removal. Moreover, this chamber should have an overflow pipe connecting to the stormwater system and some baffle walls to increase detention time, allowing more suspended solids to settle down to the bottom.

APPENDICES

**Table 3.3.2:** Inflow runoff and cistern TSS for the University of Maryland bioretention study.

| i | Date | TSS (mg/L) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 7/8/14 | 113 | 25 |
| 2 | 7/15/14 | 96 | 16 |
| 3 | 7/27/14 | 130 | 3 |
| 4 | 8/12/14 | 329 | 3 |
| 5 | 8/23/14 | 66 | 6 |
| 6 | 8/31/14 | 250 | 2 |
| 7 | 9/6/14 | 257 | 1 |
| 8 | 10/11/14 | 389 | 40 |
| 9 | 12/2/14 | 245 | 19 |
| 10 | 1/24/15 | 230 | 30 |
| 11 | 3/10/15 | 300 | 10 |
| 12 | 3/27/15 | 218 | 32 |
| 13 | 4/14/15 | 230 | 28 |
| 14 | 4/19/15 | 283 | 31 |
| 15 | 5/18/15 | 310 | 10 |
| 16 | 6/1/15 | 190 | 10 |
| 17 | 6/4/15 | 100 | 20 |
| 18 | 6/8/15 | 120 | 10 |
| 19 | 6/18/15 | 80 | 10 |
| 20 | 6/20/15 | 50 | 10 |
| 21 | 6/23/15 | 70 | 10 |
| 22 | 6/25/15 | 60 | 10 |
| 23 | 6/27/15 | 60 | 10 |
| 24 | 7/27/15 | 50 | 10 |
| 25 | 8/20/15 | 70 | 10 |
| 26 | 8/24/15 | 50 | 10 |
| 27 | 9/12/15 | 80 | 10 |

**Table 3.3.2.3:** Inflow runoff and cistern TP for the University of Maryland bioretention study.

| i | Date | TP (mg/L) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 7/8/14 | 0.330 | 0.140 |
| 2 | 7/15/14 | 0.230 | 0.160 |
| 3 | 7/27/14 | 0.380 | 0.140 |
| 4 | 8/12/14 | 0.700 | 0.160 |
| 5 | 8/23/14 | 0.230 | 0.130 |
| 6 | 8/31/14 | 0.550 | 0.150 |
| 7 | 9/6/14 | 0.630 | 0.080 |
| 8 | 10/11/14 | 0.870 | 0.150 |
| 9 | 12/2/14 | 0.950 | 0.120 |
| 10 | 1/24/15 | 0.910 | 0.150 |
| 11 | 3/10/15 | 0.321 | 0.152 |
| 12 | 3/27/15 | 0.433 | 0.133 |
| 13 | 4/14/15 | 0.255 | 0.119 |
| 14 | 4/19/15 | 1.681 | 0.208 |
| 15 | 5/18/15 | 0.423 | 0.234 |
| 16 | 6/1/15 | 0.466 | 0.222 |
| 17 | 6/4/15 | 0.260 | 0.164 |
| 18 | 6/8/15 | 0.167 | 0.152 |
| 19 | 6/18/15 | 0.716 | 0.150 |
| 20 | 6/20/15 | 0.451 | 0.159 |
| 21 | 6/23/15 | 0.471 | 0.173 |
| 22 | 6/25/15 | 0.434 | 0.254 |
| 23 | 6/27/15 | 0.700 | 0.253 |
| 24 | 7/27/15 | 0.293 | 0.204 |
| 25 | 8/20/15 | 0.531 | 0.220 |
| 26 | 8/24/15 | 0.232 | 0.183 |
| 27 | 9/12/15 | 0.648 | 0.231 |

**Table 3.3.3.3:** Inflow runoff and cistern TN for the University of Maryland bioretention study.

| i | Date | TN (mg/L) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 7/27/14 | 0.028 | 0.000 |
| 2 | 8/12/14 | 1.180 | 0.808 |
| 3 | 8/23/14 | 1.498 | 0.585 |
| 4 | 8/31/14 | 1.695 | 0.822 |

| | | | |
|---|---|---|---|
| 5 | 9/6/14 | 2.177 | 0.547 |
| 6 | 10/11/14 | 1.753 | 0.550 |
| 7 | 12/2/14 | 2.042 | 1.210 |
| 8 | 1/24/15 | 3.020 | 1.347 |
| 9 | 3/10/15 | 2.504 | 1.596 |
| 10 | 3/27/15 | 1.782 | 1.228 |
| 11 | 4/14/15 | 3.670 | 1.440 |
| 12 | 4/19/15 | 6.243 | 1.146 |
| 13 | 5/18/15 | 3.393 | 1.304 |
| 14 | 6/1/15 | 1.479 | 0.851 |
| 15 | 6/4/15 | 1.770 | 0.961 |
| 16 | 6/8/15 | 0.944 | 0.665 |
| 17 | 6/18/15 | 1.437 | 0.935 |
| 18 | 6/20/15 | 1.285 | 0.757 |
| 19 | 6/23/15 | 1.063 | 0.693 |
| 20 | 6/25/15 | 1.198 | 0.824 |
| 21 | 6/27/15 | 1.206 | 0.733 |
| 22 | 7/27/15 | 3.513 | 2.376 |
| 23 | 8/20/15 | 4.152 | 1.828 |
| 24 | 8/24/15 | 3.353 | 1.991 |
| 25 | 9/12/15 | 3.251 | 1.682 |

**Table 3.3.4.3:** Inflow runoff and cistern EC for the University of Maryland bioretention study.

| i | Date | EC @ 25°C (mS/cm) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 12/2/14 | 0.09 | 0.10 |
| 2 | 3/10/15 | 2.17 | 4.44 |
| 3 | 3/27/15 | 2.02 | 0.66 |
| 4 | 4/14/15 | 1.92 | 0.75 |
| 5 | 4/19/15 | 1.97 | 0.53 |
| 6 | 5/18/15 | 0.09 | 0.14 |
| 7 | 6/1/15 | 0.11 | 0.11 |
| 8 | 6/4/15 | 0.07 | 0.07 |
| 9 | 6/8/15 | 0.05 | 0.09 |
| 10 | 6/18/15 | 0.051 | 0.110 |
| 11 | 6/20/15 | 0.063 | 0.121 |
| 12 | 6/23/15 | 0.070 | 0.123 |
| 13 | 6/25/15 | 0.043 | 0.118 |
| 14 | 6/27/15 | 0.055 | 0.115 |

| | | | |
|---|---|---|---|
| 15 | 7/27/15 | 0.084 | 0.132 |
| 16 | 8/20/15 | 0.100 | 0.117 |
| 17 | 8/24/15 | 0.064 | 0.122 |
| 18 | 9/12/15 | 0.100 | 0.115 |

**Table 3.3.4.4:** Inflow runoff and cistern pH for the University of Maryland bioretention study.

| i | Date | pH | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 12/2/14 | 7.16 | 7.17 |
| 2 | 3/10/15 | 7.67 | 7.52 |
| 3 | 3/27/15 | 7.70 | 7.52 |
| 4 | 4/14/15 | 7.68 | 7.51 |
| 5 | 4/19/15 | 7.56 | 7.54 |
| 6 | 5/18/15 | 6.21 | 5.86 |
| 7 | 6/1/15 | 6.66 | 6.11 |
| 8 | 6/4/15 | 7.49 | 7.33 |
| 9 | 6/8/15 | 7.22 | 6.96 |
| 10 | 6/18/15 | 7.34 | 7.13 |
| 11 | 6/20/15 | 7.52 | 7.22 |
| 12 | 6/23/15 | 7.37 | 7.11 |
| 13 | 6/25/15 | 7.40 | 6.99 |
| 14 | 6/27/15 | 7.27 | 7.06 |
| 15 | 7/27/15 | 6.60 | 6.37 |
| 16 | 8/20/15 | 7.06 | 6.45 |
| 17 | 8/24/15 | 6.97 | 6.83 |
| 18 | 9/12/15 | 7.63 | 7.03 |

**Table 3.4.1.2:** Inflow runoff and cistern copper for the University of Maryland bioretention study.

| i | Date | Cu (µg/L) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 8/12/14 | 21.2 | 20.0 |
| 2 | 8/23/14 | 14.7 | 27.8 |
| 3 | 8/31/14 | 9.1 | 24.6 |
| 4 | 9/6/14 | 16.2 | 28.8 |
| 5 | 12/2/14 | 25.0 | 13.0 |
| 6 | 3/10/15 | 11.3 | 2.7 |
| 7 | 3/27/15 | 26.7 | 26.1 |
| 8 | 4/14/15 | 37.5 | 30.5 |

| | | | |
|---|---|---|---|
| 9 | 4/19/15 | 72.2 | 81.6 |
| 10 | 5/18/15 | 9.1 | 10.8 |
| 11 | 6/1/15 | 23.5 | 5.03 |
| 12 | 6/4/15 | 7.18 | 18.2 |
| 13 | 6/8/15 | 7.39 | 4.66 |
| 14 | 6/18/15 | 35.7 | 8.4 |
| 15 | 6/20/15 | 8.0 | 6.4 |
| 16 | 6/23/15 | 13.9 | 8.6 |
| 17 | 6/25/15 | 7.3 | 3.4 |
| 18 | 6/27/15 | 12.3 | 2.7 |
| 19 | 7/27/15 | 13.1 | 3.2 |
| 20 | 8/20/15 | 22.1 | 6.2 |
| 21 | 8/24/15 | 14.6 | 8.9 |
| 22 | 9/12/15 | 16.0 | 3.1 |

**Table 3.4.2.2:** Inflow runoff and cistern lead for the University of Maryland bioretention study.

| i | Date | Pb (µg/L) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 6/1/15 | 5.15 | 1 |
| 2 | 6/4/15 | 15.4 | 1.4 |
| 3 | 6/18/15 | 5.35 | 0.72 |
| 4 | 6/20/15 | 1.89 | 0.13 |
| 5 | 6/23/15 | 3.72 | 0.56 |
| 6 | 6/25/15 | 3.93 | 0.34 |
| 7 | 6/27/15 | 3.42 | 0.32 |
| 8 | 7/27/15 | 5.38 | 0.30 |
| 9 | 8/20/15 | 6.11 | 5.07 |
| 10 | 8/24/15 | 4.59 | 0.28 |
| 11 | 9/12/15 | 5.03 | 0.41 |
| 12 | 9/29/15 | 4.32 | 0.51 |
| 13 | 10/2/15 | 4.52 | 0.43 |
| 14 | 10/9/15 | 5.34 | 0.72 |

**Table 3.4.3.2:** Inflow runoff and cistern zinc for the University of Maryland bioretention study.

| i | Date | Zn (µg/L) | |
|---|---|---|---|
| | | Inflow | Cistern |
| 1 | 8/12/14 | 15.4 | 4.5 |
| 2 | 8/23/14 | 5.9 | 2.0 |
| 3 | 8/31/14 | 1.2 | 3.7 |
| 4 | 9/6/14 | 5.1 | 7.9 |
| 5 | 12/2/14 | 157.0 | 15.0 |
| 6 | 3/10/15 | 8.7 | 6.7 |
| 7 | 5/18/15 | 12.4 | 16.2 |
| 8 | 6/1/15 | 213 | 10.5 |
| 9 | 6/4/15 | 37.5 | 18.2 |
| 10 | 6/8/15 | 40.9 | 2.57 |
| 11 | 6/18/15 | 65.9 | 19.1 |
| 12 | 6/20/15 | 23.0 | 14.8 |
| 13 | 6/23/15 | 72.0 | 14.2 |
| 14 | 6/25/15 | 40.2 | 12.2 |
| 15 | 6/27/15 | 66.2 | 12.3 |
| 16 | 7/27/15 | 45.3 | 11.8 |
| 17 | 8/20/15 | 121.0 | 17.4 |
| 18 | 8/24/15 | 87.6 | 19.5 |
| 19 | 9/12/15 | 78.5 | 24.0 |

**Table 3.6.1:** Statistic tests for the University of Maryland bioretention study.

| | t-Test | | Wilcoxon Sign Rank Test | | |
|---|---|---|---|---|---|
| Parameters | t-Test | α = 0.05 | \|W\| | W0.05 | Decision |
| TSS | 3.73E-08 | Reject Ho | 378 | 98 | Reject Ho |
| TP | 3.00E-06 | Reject Ho | 378 | 98 | Reject Ho |
| TN | 1.10E-05 | Reject Ho | 325 | 81 | Reject Ho |
| Cu | 1.39E-01 | Accept | 89 | 58 | Reject Ho |
| Pb | 9.26E-05 | Reject Ho | 105 | 17 | Reject Ho |
| Zn | 1.76E-03 | Reject Ho | 172 | 40 | Reject Ho |
| EC | 7.35E-01 | Accept Ho | 72 | 35 | Reject Ho |
| pH | 7.00E-06 | Reject Ho | 169 | 35 | Reject Ho |

**Table 3.6.2:** Water qualities of UMD tap water, average cistern, and data from Potomac Water Filtration Plant 2014.

| Tap Water | TP, (mg/L) | TN, (mg/L) | Cu, (µg/L) | Pb, (µg/L) | Zn, (µg/L) |
|---|---|---|---|---|---|
| 8/22/15 | 0.27 | 1.68 | 159 | 1.68 | 168 |
| 8/26/15 | 0.30 | 2.10 | 172 | 0.39 | 36 |
| 9/12/15 | 0.26 | 1.74 | 166 | 0.72 | 81 |
| 9/30/15 | 0.28 | 1.83 | 169 | 0.85 | 74 |
| 10/20/15 | 0.28 | 1.90 | 175 | 0.86 | 79 |
| Average Tap | 0.28 | 1.85 | 168 | 0.90 | 88 |
| Potomac, 2014 | 0.29 (< 0.33) | 1.60 (1.2 – 3.1) | <2 (< 2 – 8) | n/d | 2 (< 2 – 3) |
| Average Cistern | 0.17 | 1.08 | 15.7 | 1.21 | 12.2 |

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