A PRELIMINARY ASSESSMENT OF WATER QUALITY AT THE RAINWATER-HARVESTING BASIN LEVEL IN AN URBAN SEMI-ARID ENVIRONMENT

By

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Abstract

One of the anticipated benefits of green infrastructure is the capture in curb-cut basins of stormwater runoff that has accumulated urban contaminants as it runs over asphalt and pavement. These contaminants may include motor oil, pathogens, and sediments. The desert-tolerant vegetation and soils within these residential rainwater-harvesting basins are expected to improve water quality by capturing these contaminants that would have otherwise flowed into local washes and recharged into the groundwater. This project reports on a preliminary comparative study of stormwater runoff quality in two Tucson washes (High School Wash and Bronx Wash) that receive runoff from neighborhoods containing rainwater-harvesting basins. The primary goal of this research project was to design a water-sampling device and protocol that accounts for variability in basins' soil composition, successfully filters debris and soil, and collects enough sample size for water quality analysis. The secondary research goal was to conduct a preliminary comparative assessment at the neighborhood wash scales to quantify the effects of green infrastructure basins in urban areas.

Introduction

Stormwater runoff is viewed as a renewable water resource; particularly in urban semi-arid environments where rainfall is scare and groundwater resources are becoming ever more exhausted. Green infrastructure (GI) refers to the integration of ecological systems that are natural or semi-natural, spanning both public and private realms to replace or augment more traditional grey infrastructure systems that manage stormwater (Wolf, 2014; Norton et al., 2015). GI detention ponds, also known as bioswales, capture and infiltrate stormwater runoff, create small ecosystems in urban environments, and improve stormwater quality. Furthermore, vegetated bioswales are recommended by the US Environmental Protection Agency (EPA) as best management practices to clean pollutants and improve water quality Xiao & McPherson (2011). In Tucson neighborhoods, small bioswales are generally 5' x 3' x 3', and are located along streets where water can naturally run into them via curb cuts. With climate change bringing longer and drier rainy seasons in semi-arid environments it is important to maximize the use of the natural infrastructure to help protect our groundwater quality and supply.

In the semi-arid city of Tucson, Arizona, Gallo et al. (2013b) quantified the concentration of nitrogen and phosphorous, along with other chemical analysis, to assess the water quality of stormwater runoff in the Tucson Metropolitan area. The samples collected by Gallo et al. (2013b) were collected from several washes, and not from directly within the bioswales. There have been a few other U.S. researchers who have collected water samples from within bioswales (e.g. Xiao & McPherson (2011), and Purvis et al. (2018)). The latter collected samples from trench-like bioswales, and implemented surface-subsurface sampling techniques that involved storage tanks with pumps or autosamplers. Xiao & McPherson (2011) created a trench-like bioswale backfilled with a variety of engineered soils to improve infiltration and reduce stormwater runoff. The engineered soils provided better aeration and drainage for tree growth compared with the control's compacted urban soil. They used a sophisticated water sampling technique using a subsurface water tank, flow pump, flow divider, water sample container, and datalogger. An analysis of their water samples revealed that their bioswale design decreased pollutant loading by 95.4%.

A simple water sampling technique at the bioswale scale has not been developed in the Tucson metropolitan area. Therefore, it is unknown how or if the water quality changes substantially in the basins located near Bronx and High School Washes. Quantifying bioswale basin utility by analyzing how stormwater chemistry varies spatially can provide further insight into the value of green infrastructure in semi-arid environments.

The point of this research project was to develop small-scale catchment devices capable of collecting, and effectively filtering stormwater runoff. Furthermore, the water-capturing devices, which are essentially mini stilling wells, needed to capture a volume substantial enough to run samples using Smartchem discrete analyzers to measure nitrate, nitrite, and phosphorous content via colorimetric reactions. There were several challenges associated with collecting water samples from directly within these bioswales. In southwestern Arizona most of the rainfall occurs during the summer monsoon season, and these conditions involve scattered storms, high wind speeds, and intense precipitation rates. Furthermore, the coarse and varied soil composition of the bioswales along with the vegetation, varies greatly from basin to basin. After developing the sampling devices, a preliminary comparative study was executed between the basins and the basin-scale washes.

Literature Review

Nitrogen is abundant and found naturally in the environment, but can also be introduced directly into ecosystems via sewage and fertilizers, and indirectly via automobile compounds and the combustion of fossil fuels. Phosphorous is an essential element for plant life and is a common constituent of sewage, industrial effluent, and fertilizers. In addition, phosphorous adheres to soil particles and thus travels through surface water bodies via runoff; it also can migrate with groundwater flows. While nitrogen and phosphorus are a fundamental part of animal and plant growth, an overabundance of these nutrients can have adverse effects on water quality. High concentrations of both constituents result in oxygen deprivation in water bodies, clogged water intakes, and algal blooms. Furthermore, an excess of nitrate in drinking water can restrict the oxygen transport in the bloodstream of young infants or young livestock (USGS Circular 1225). In urban semi-arid environments, it is common for nitrogen to build up over time in high concentrations. Solute accumulation during dry seasons in semi-arid areas results in an increased concentration of streamflow solutes and sediment transport. Furthermore, in desert watersheds solute concentration is exacerbated by sparse vegetation, varied topography, and rapid urbanization (Jiang et al. 2015).

Green infrastructure has the potential to improve the environmental impact due to climate change and urbanization, with health co-benefits. Rapidly growing urban regions in the West and Southwest US have been classified as the most persistent hot spots associated with high precipitation variability and high temperatures, as a result of climate change (Jiang et al. 2015). Stormwater drains and pipes tends to rapidly drain stormwater runoff, which thus decreases the amount of moisture captured in an urban landscape, which in turn reduces evapotranspiration and increases the sensible heating from the urban atmosphere (Norton et al. 2015. Furthermore, several studies have concluded that higher temperatures at night limits a person's ability to recover from daytime heat stress (Norton et al., 2015). Therefore, GI can help reduce the heat island effect, which is becoming more pronounced with climate change, and can help reduce human heat stress. Studies have also shown that exposure to natural settings including trees, green spaces, grass, and flowers has positive effects on mental health, recovering patients, and active living (Wolf, 2014). The positive effects observed in these studies range from reduced stress and mental fatigue, decreased recidivism rates in prisons who participate in horticulture, and increased healthy weight status for people of all ages. The effect of GI, including streets that are lined with trees, has been shown to promote and encourage outdoor activity in people of all ages (Wolf, 2014). These studies indicate that GI has both environmental and social benefits.

Other studies by Halle et al. (2015) and Rockhill (2017) provide further insight on GI basin soil properties and biogeochemical reactions. Hale et al. (2015) observed changes in GI design in the semi-arid city of Phoenix, Arizona. The variation in infrastructure design was compared to changes in fluxes of dissolved nitrogen, phosphorous, and organic carbon. From 1995-2010 designs in stormwater infrastructure shifted from pipes and human-made channels to natural washes and retention basins. Results were consistent with other studies that found that retention basin density decreased runoff, while imperviousness increased runoff; which in turn increased nutrient and dissolved organic carbon (DOC) delivery. Tyler (2017) indicated that previous studies have shown that bioswales can sequester both dissolved and suspended constituents such as nitrogen, phosphorus, carbon, arsenic, cadmium, chloride, chromium, copper, E. coli, fecal coliform, lead, mercury, oil and grease, total suspended solids, and total zinc. This research helps inform the utility of the current research project, and serves as a guide for water quality assessment at the GI basin level.

Two studies by Gallo et al. (2013a & 2013b) have addressed urban hydrology green infrastructure, specifically in the semi-arid environment of Tucson, Arizona. Gallo et al. (2013b) identified patterns in runoff magnitude and solution chemistry of urban catchments located in the Tucson metropolitan area. Furthermore, Gallo et al. (2013a), demonstrated that urbanization increases the frequency and duration of runoff delivered to areas of focused recharge. Runoff rainfall thresholds and higher runoff frequencies are likely attributed to percentage of an area’s imperviousness, road densities, and presence of impervious channels. Time-to-peak discharge did not vary between urban and underdeveloped areas, indicating that monsoon runoff does not vary much in response to urban development, but does increase with respect to stormwater drainage systems and outlets. While imperviousness results in higher runoff, which effectively serves as a tool for transporting more water that can be used for recharge, it also results in higher concentrations of solutes and contaminants that can reach the groundwater. This indicates that managing stormwater runoff before it reaches local washes and recharge areas may influence groundwater quality.

Site description

Figure 1 below outlines the research sites located in the Bronx (BX) and High School (HS) Washes in the semi-arid city of Tucson, Arizona. These research sites were used in previous GI investigations by Anderson (2018).

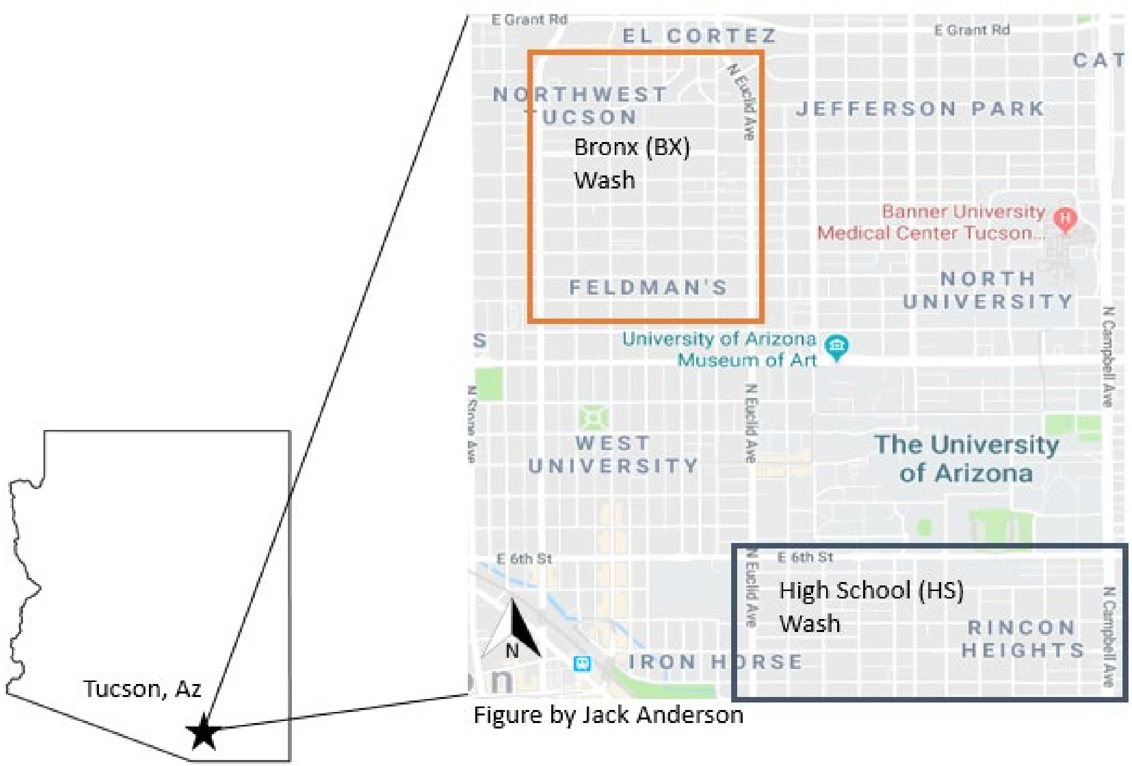

Figure 1. Location of Bronx and High School Washes in Tucson, AZ

Anderson's bioswale soil composition, location, and soil properties (see Appendix I) were used as criteria to select GI basins for the current study. Topsoil material was the first property that was used to select bioswales since water-capturing devices would be used for the study, and needed to be easily installed in the soil. Bioswale material varied from bare soil, fine rock, organic material, and mixed compositions. Bare soil, organic material, and mixed material were preferred due to predicted ease of well installation. After mapping all the well sites into ArcGIS, water holding capacity (WHC) and hydraulic conductivity values were assessed to determine which bioswales would be valuable for this study. Bioswales with both high WHC and high hydraulic conductivity were identified.

Figure 2 includes hydraulic conductivity data of all the bioswales used in Anderson's (2018) study. Despite various bioswales in the top half of Figure 2 (i.e. Bronx Wash sites) that are shaded in blue, indicating higher hydraulic conductivity, the bioswales in yellow and orange tones were used for this study. This choice was made based on the known frequency of stormwater runoff collected in the bioswales in the yellow-orange region, and older bioswale designs in the blue regions. It is also important to recognize that the distribution of hydraulic conductivities in the bioswales located in Bronx Wash (the top half of Figure 2) is more scattered than those used in High School Wash. The hydraulic conductivity values range from 1.65×10^{-5} m/s to 1.97×10^{-4} m/s. Hydraulic conductivity values are relevant because the infiltration capacity of the collective bioswales ultimately determines their potential effectiveness at reducing urban runoff; however, there is significant variation in bioswale infiltration capacity despite relatively similar soil properties (Anderson 2018), and this is evident in Figure 2. Furthermore, the presence of vegetation and a rocky surface may generally improve infiltration rates but differing degrees of mulch decomposition can have mixed effects on overall hydraulic conductivity (Anderson 2018).

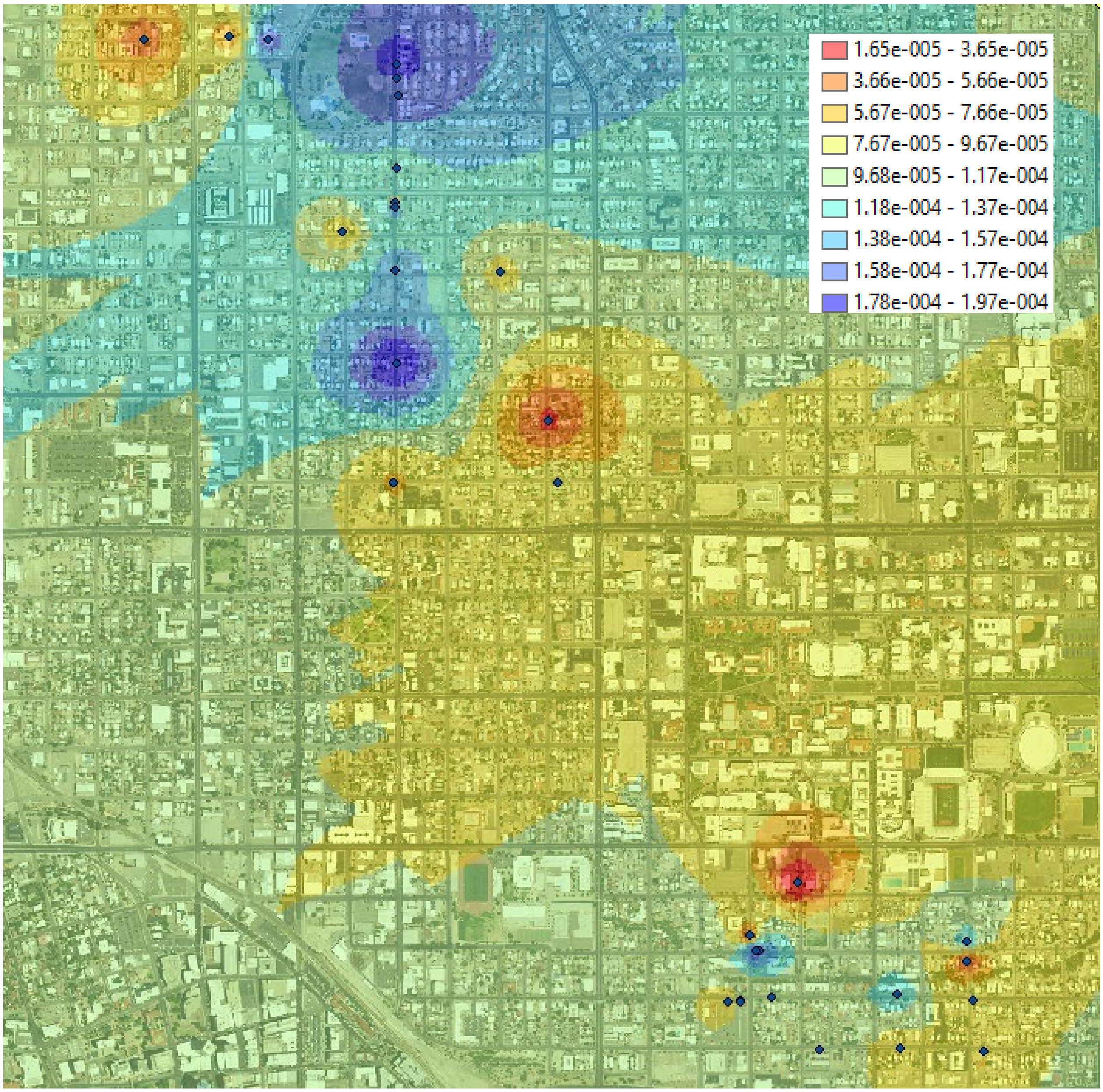

Figure 2. Hydraulic conductivity distribution of bioswales in BX (north cluster of sites) and HS (southeastern cluster of sites) Washes. Hydraulic conductivity is reported in meters per second (m/s) (data courtesy of Anderson, 2018).

Gravimetric soil moisture, calculated by Rockhill (2017) was used as a proxy for WHC, and the implied WHC of individual bioswales is shown in Figure 3. Gravimetric soil moisture was calculated by dividing the mass of water over the mass of the dry soil, with values ranging from 28.5% (rounded to 29% in the figure) to 119% with the areas of greatest implied WHC shaded in blue. Values of gravimetric soil moisture greater than 100% - which are of course not physically possible – indicate measurement errors that are attributable to macropores created by vegetation, bioturbation (e.g. root paths or small animal burrows, especially worms or insects), or directly from soil organic matter, as opposed to the actual mineral soil (Anderson 2018; Rockhill 2017). Bioswales with greater implied WHC were preferred in this study to optimize the opportunity of water-capturing devices to collect samples within the basins.

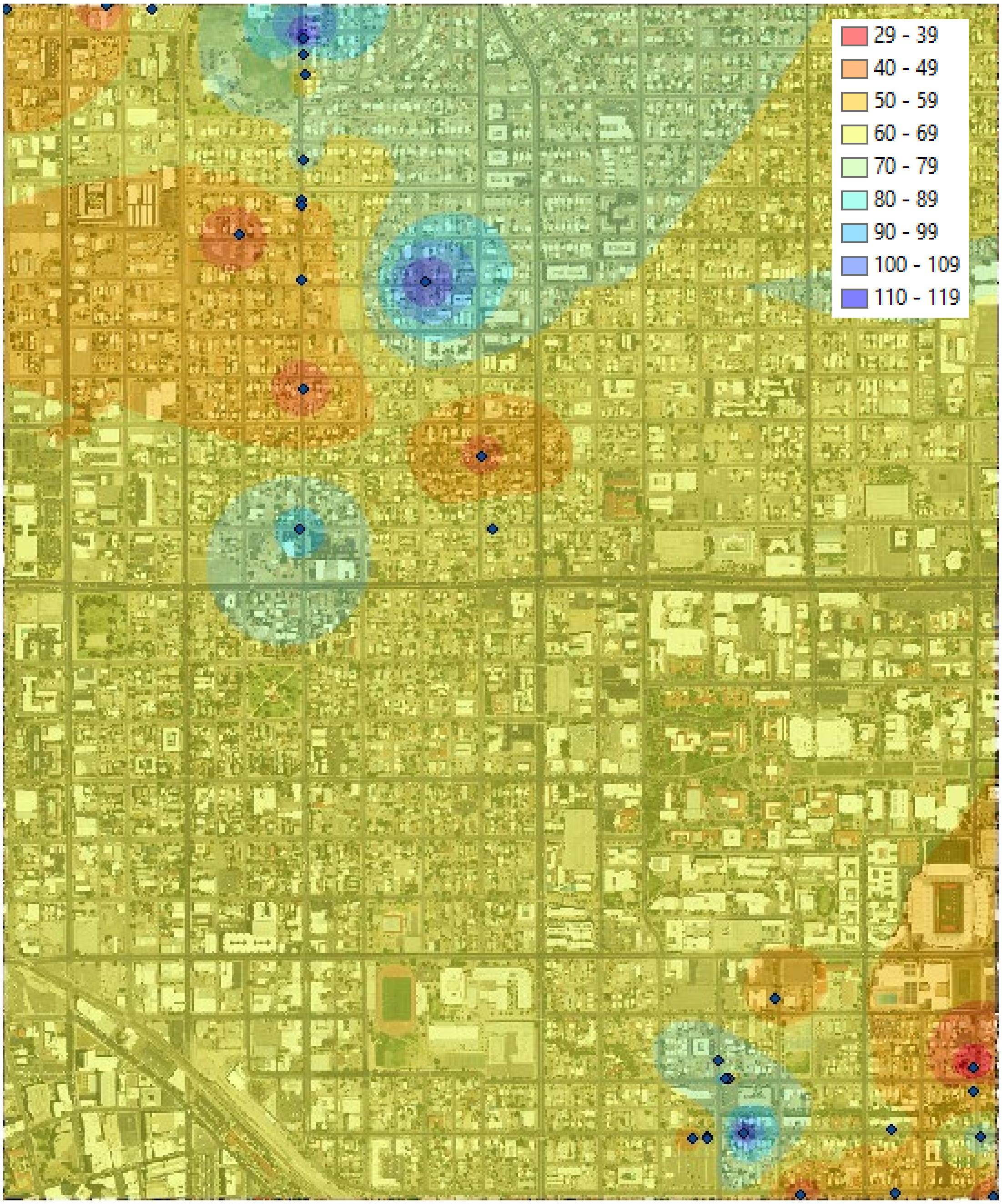

Figure 3. Implied water-holding capacity distribution of bioswales in BX (north cluster of sites) and HS (southeastern cluster of sites) Washes. Gravimetirc soil moisture was used as a proxy to infer water-holding capacity (data courtesy of Anderson, 2018).

More importantly, the bioswales in both HS and BX Washes encompassed sufficient area for a preliminary spatially-distributed chemical analysis. After identifying bioswales with high hydraulic conductivities and water holding capacities, a field reconnaissance of the sites was necessary to confirm coordinates and to identify potential challenges. Some of these challenges included imprecise coordinate data for the bioswales, and outdated bioswale photos and descriptions. Effective well installation was also a potential challenge because of the wide variety of top soil composition at the study sites. The final basin and bioswale locations were mapped using Google Maps (see Figure 4) for ease of sample collection, and location sharing. By using google maps the bioswales were identified using coordinates and basin ID names that are accessible to the public and can be located with a direct path from the user's location.

Within the basins there are flow-through (FT) and terminal (TR) bioswales. Flow-through bioswales have two curb cut-outs while terminal bioswales have one curb cut-out. The FT and TR basins are simply differences in basin designs. The inclusion of basins with both one and two curb cut-outs may have contributed additional variability to the results, but for the purposes of the study, this was deemed less important than the hydraulic conductivity, WHC, and spatial distribution of the sites.

The bioswales in Bronx Wash have a weaker spatial distribution for several reasons. First, the bioswales in Bronx Wash appeared to have a greater number of bioswales of an older design, with a lack of curb cut-outs. Furthermore, bioswales BX TR 25, 26, and 1 consistently capture high volumes of water (Anderson, 2018).

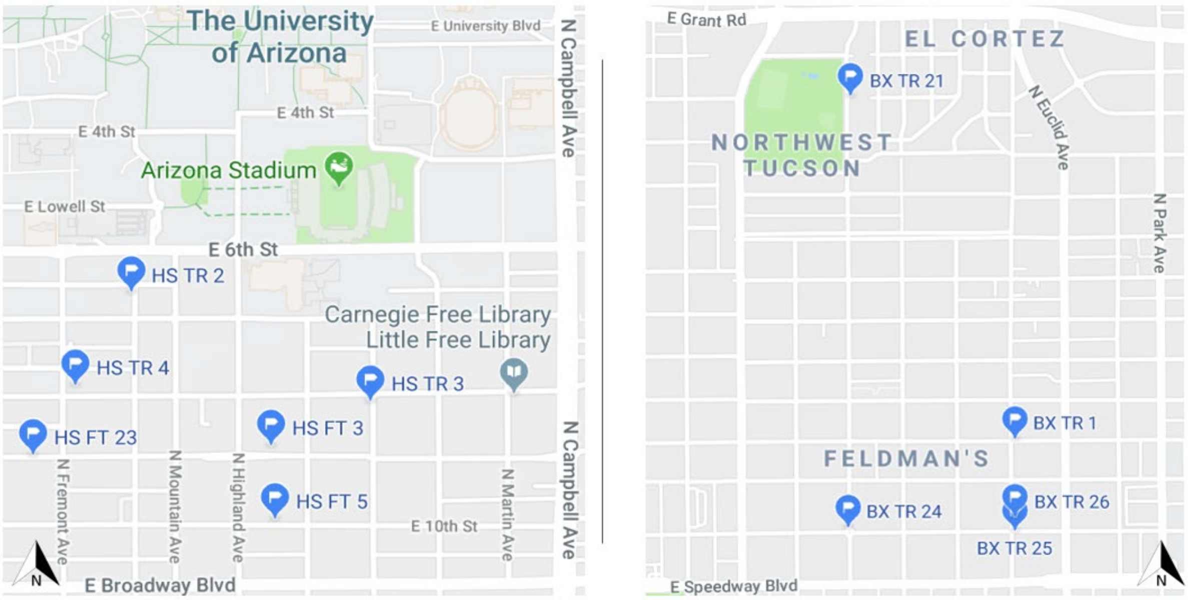

Figure 4. Basin and bioswale study site locations within the High School (left) and Bronx (right) Wash areas.

Methods and Materials

GI designs – e.g. bioswales – incorporate vegetation to manage stormwater runoff. While the vegetation helps distill contaminated water, it was also an obstacle in the water-capturing device installation and design. The water sampling devices were designed to mitigate the negative effects of inhibiting the flow of runoff into the bioswales. Some of the anticipated challenges included: stilling well stabilization during storm events; bioswale soil and elevation heterogeneity; and effectively filtering out sediment to prevent changes in water chemistry. Well stabilization was a concern because of strong winds, and heavy stormwater runoff during storm events that could potentially displace the wells or wash them away. Furthermore, variation in the soil surface – ranging from sandy clay loam to coarse rock - made it difficult to design a stilling well sampling device that worked in a wide variety of bioswale conditions.

Finally, since vegetation (e.g. leaf litter, and weeds) is often found in bioswales, and stormwater runoff also carries debris, it was anticipated that there would need to be a way to filter the water during stormwater runoff capture. Therefore, the main factors considered in the stilling well design were to: i) minimize the impact on the bioswales, while remaining structurally sound during storm events; ii) effectively filter out debris; and iii) collect enough water for chemical analyses.

Gallo et al. (2013a) collected stormwater runoff at the neighborhood wash scale and used automatic water samplers (ISCO 6712, Teledyne Technologies, Lincoln, Nebraska[1]) installed at the outlet of each catchment. Approximately 250 mL of water was used to successfully filter and store samples that were tested for cations, anions, nitrogen, and phosphate. Based on the successful results reported by Gallo et al. (2013a), it was determined that the water-capturing devices designed for the current study should capture about 250 mL from each bioswale. Figure 5 illustrates the initial water sampling device used in this study. To address the stabilization of the capturing device and minimize impact on bioswale conditions, it was determined that once the capturing device was installed it should remain in the basin during the duration of the rainy seasons. More specifically, each mini stilling well was not removed after each storm event. Instead, the device was designed to accommodate a replaceable water sampling cup. This sampling cup was removed and replaced with a new, clean cup prior to each new storm event. The replacement cups also mitigated risk of contamination and/or residue from previous storms. Each device was embedded to a depth of three inches to provide sufficient stabilization to avoid being toppled and/or washed away during storms. A drainage cap was used to allow water to enter the device from the top more quickly, while still filtering out some debris. In addition, holes were drilled into the side of the stilling wells to allow water to run into the device laterally during smaller storm events that may not necessarily fill the entire basin, and

[1] Throughout this document, brand names are included for information only, and do not constitute an endorsement by the author or The University of Arizona.

therefore would not flow over the top of the collection devices. The stilling wells' compact dimensions used were chosen to mitigate the impact of the well's presence in the bioswale.

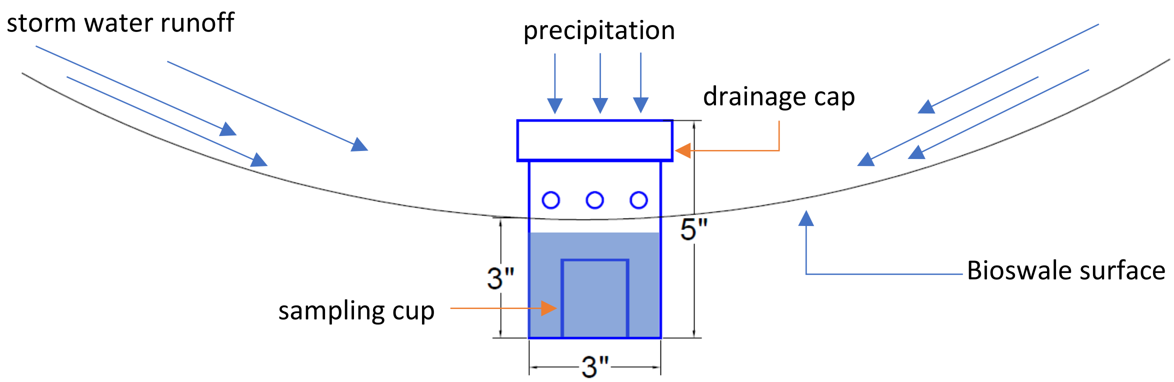

Figure 5. Mini stilling well design

PVC pipe was used for the construction of the water-sampling devices because it is so easy to cut, drill, and assemble different components of the same material. . Five-inch segments of 3-inch diameter PVC pipe was used to construct the water-sampling devices. On each pipe segment, holes were drilled using a 3/16th-inch drill bit ¾-inch from the top edge (see Figure 6a). A metal file was used to remove burrs on the cut ends of PVC pipe. It was determined that a base or cover was needed to hold the removable sampling cup in place. A Tom-Kap^{TM} is a clean-out adaptor fitting that is cemented inside a pipe to provide a flush-finished cleanout for drain, waste, and vent systems. A 3–inch diameter Tom-Kap^{TM} was used to seal the bottom of the PVC pipe, while also allowing the water to drain out of the well, and to provide a base for the sampling cups. The diameter of the 125 ml sampling cups allows them to fit securely along the inside wall of the Tom-Kap^{TM}.

After initial testing was conducted, two stilling wells were installed per basin to collect a total of 250 ml if stormwater runoff samples. A 3" to 4" universal round grate was connected to the top of the well to help filter out debris. However, the drainage cap alone did not seem effective enough to filter out finer sediments. Therefore, silver fiberglass screen mesh was cut into 4” x 4” pieces that were cross hatched and secured using rubber bands to the top of the removable sampling cups (Figures 6 b and c). Initially duct tape was used to hold the mesh in place, but the duct tape was flimsy and difficult to work with. Instead, the screen mess was held in place using rubber bands. Additionally, screen mesh was folded around the interior and exterior circumference of the well, ensuring that the side holes were covered.

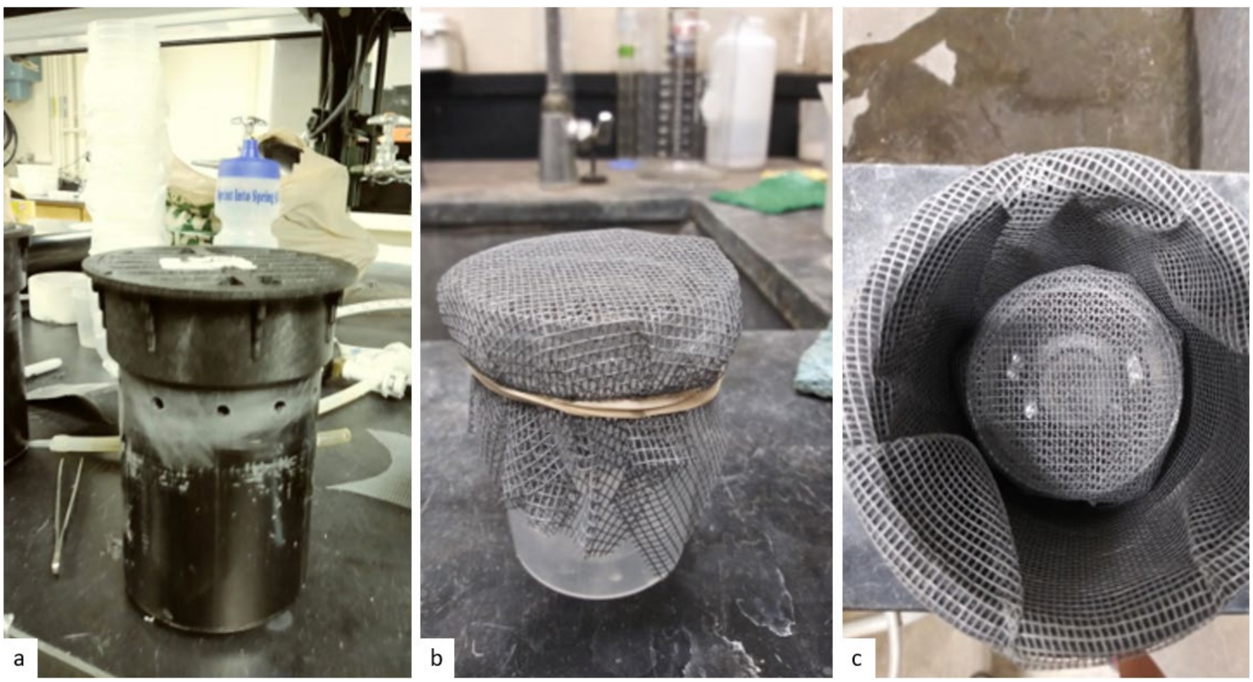

Figure 6. a) well casing and drain b) sampling cup c) cup and screen mesh around and inside of the well

After cutting the 3” PVC pipe into 5” segments, three pilot wells were created to determine the ideal number of holes to drill along the sides of the wells to optimize sediment filtering. For each pilot well, holes were drilled ¾” from the top. One well had 0.5-inch hole spacing, another had 1-inch hole spacing, and the third had 2-inch hole spacing. Stormwater runoff simulations were conducted using a garden hose with a flow path leading from the street into the basin (see Figure 7a). It was determined that the 2-inch hole spacing would be used because there was not a significant difference in the amount of sediment accumulated in each well. Furthermore, variation in elevation, and basin location made it difficult to determine which hole-spacing arrangement collected the least amount of sediment. The wells were arranged (left to right) with 0.5” hole spacing to 2” hole spacing (see Figure 7b).

Figure 7. a) Initial runoff simulation using garden hose to stimulate runoff. b) well placement inside basin for runoff simulation.

Prior to an anticipated storm event, the three protype stilling wells were installed in basin BX TR 1 (see Figure 8a). This basin was chosen based on the high frequency of rainfall events observed by Anderson (2018). Trowels were used to create 3” x 3” holes in the basin. The wells were installed with only the top two inches exposed above ground to collect and filter stormwater runoff. When samples were retrieved, the ground around the mini stilling wells had eroded, and they were found resurfaced and toppled over (see Figure 8b).

Figure 8. a) Before storm event and initial field testing. b) After the storm event it was apparent that the wells had had been eroded out of their initially installed positions, and appeared as resurfaced and toppled wells.

Installing the mini stilling wells three inches into the ground did not provide enough structural support to withstand the material’s buoyance, stormwater flow rates, and/or strong winds. To rectify this problem, the wells were zip-tied to 6-inch aluminum gardening stakes. (see Figure 9a). Two to four aluminum stakes were zip-tied to each stilling well (see Figure 9b). The stakes were hammered into the soil, which helped keep the wells in place and prevented them from being toppled over and/or carried away by flow. However, many aluminum stakes were damaged as they were hammered into the coarse, often rocky material in most of the bioswales. Several attempts and multiple aluminum stakes (e.g. 2-5) were required to reinforce the wells.

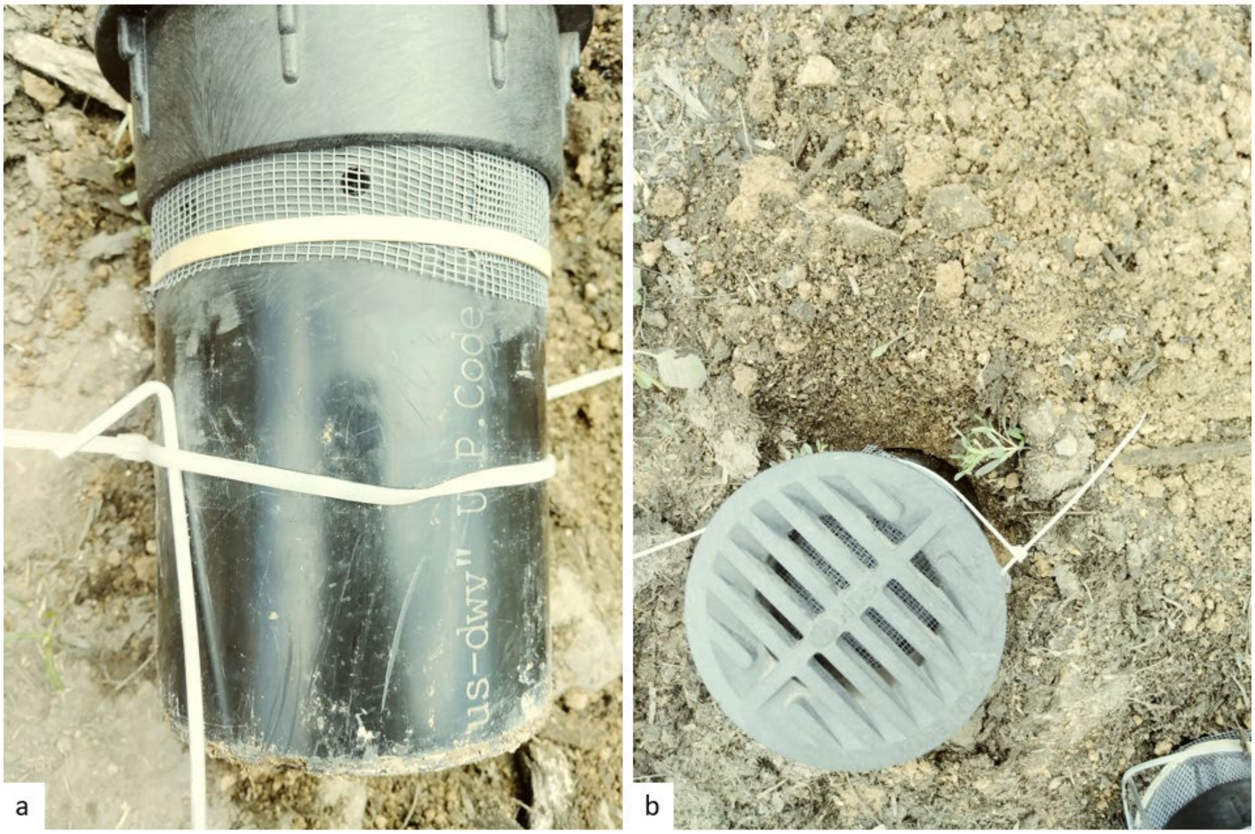

Figure 9. a) Aluminum stakes attached to stilling well. b) well installation with stakes

Anderson (2018) classified the bioswales – including High School and Bronx Washes -- based on their topsoil (see Table 1). The bioswales in this study fall into Anderson's (2018) classes 1, 2, 4, and 5. Classes 1, 2, and 4 have low to medium density of large rocks, intact or decomposed organic mulch, and varying degrees of plant density. Class 5 consists of a dense top layer of gravel with no organic mulch, and little to low plant presence.

Table 1. Anderson's (2018) qualitative descriptors for bioswale classification

Group	Primary Descriptors
Class 1	Medium density of large rocks, intact organic mulch and leaf litter, low to medium plant presence
Class 2	Medium density of large rocks, generally decomposed organic mulch and litter, medium to high plant density, with mature shrubs and trees
Class 3	High density of large rocks (covers most of soil), no organic mulch, medium plant density with some mature succulents
Class 4	Low density of large rocks, decomposed organic mulch, no or few plants present
Class 5	Dense top-layer of gravel, no organic mulch and little to no plant presence
Class 6	Homogenous, compacted sandy soil with no mulch or plant presence
Class 7	Thick, partially decomposed organic mulch layer with little to low density of large rocks
Control	Unmodified soil, typically compacted without any top layer or vegetation

Throughout the year more basins were included in the study once the well design and functionality were improved. Ultimately the project was successfully expanded to gain a wide spatial set of data in both washes. The following data from Anderson (2018) were used to select the following 11 bioswale study sites (see Table 2; the full data set is included in Appendix 1). Most of the bioswales in the Bronx Wash were Class Types 1, 2, and 4. The basins in High School Wash contained three Class Type 5 basins.

Table 2. Bioswale study site data

Site	Soil Type	Soil Organic Matter %	Implied WHC re: θg	K (m/s)	Topsoil	Class Type
BX TR 1	Sandy Loam	4.59	46.3	3.28E-05	organic	4
BX TR 21	Sandy Loam	16.41	118.7	1.94E-04	organic	1
BX TR 24	Sandy Loam	11.71	81.3	7.50E-05	mix	2
BX TR 25	Sandy Clay Loam	8.91	64.9	8.55E-05	mix	2
BX TR 26	Sandy Clay Loam	5.64	49.9	1.60E-04	organic	1
HS FT 23	Sandy Loam	6.12	51.9	3.83E-05	--	5

HS FT 3	Sandy Loam	8.12	60.2	1.31E-04	bare	4
HS FT 5	Sandy Clay Loam	4.59	49.1	8.21E-05	mix	2
HS TR 2	Sandy Clay Loam	6.82	50.8	1.64E-05	fine rock	5
HS TR 3	Sandy Loam	7.08	55.6	3.28E-05	fine rock	5
HS TR 4	Sandy Loam	10.03	54.2	1.64E-04	bare	4

Within 24-hours following a storm event, each of the sites were visited to check for and collect water samples, but enough time was allowed for the water to infiltrate in the basin The basin ID, visible degree of basin saturation, well stability, and samples collected were included in field notes. These notes were later used to determine basin sample collection frequency (addressed in the results). During the sampling retrieval process kitchen tongs were used to remove the sampling cup from the mini stilling well. The cup placement, and depth inside the stilling wells made it difficult to retrieve the samples without loss of the sample, or without dislodging the stilling wells from their stakes in the bioswales. Each sample cup was sealed with a lid, labeled with the basin ID and storm event, and taken back to the lab. The sampling cups and mesh around the cups were replaced after every storm event to prevent sample contamination. Nitrile gloves were used during the sampling process for personal hygiene and to prevent sample contamination.

The samples were collected using the following methods used in Gallo et al. (2012), which quantified the effects of stream channels on stormwater quality in the Tucson metropolitan area. The runoff and rainfall sample aliquots for carbon and nutrient analysis were filtered through a 0.7 µm Whatman glass fiber filters and stored in pre-combusted amber glass bottles at 4˚C. Anion and stable isotope analyses involved filtering the samples through a 0.45 µm

Millipore membrane filter. Filtrate for anion analysis was stored in sterile high-density polyethylene (HDPE) plastic bottles at 4 °C. Given time and resource constraints, samples from only three of the earliest storm events were used to determine total nitrogen (TN) and non-purgeable organic carbon (NPOC). The samples used for water quality analysis were the ones collected from bioswales BX TR 1, BX TR 25, and BX TR 26. TN and NPOC were determined by high temperature combustion and chemiluminescence and non-dispersive infrared analysis, respectively (Shimadzu TOC-Vcsh/TNM-1, Columbia, MD) (Gallo et al. 2012).

Results

By October 1, 2018 stilling wells were installed in five bioswales located in Bronx Wash. Figure 11 shows the design and conditions of the bioswales used in the Bronx Wash locations. Bioswales BX TR 25 and BX TR 26 include images of the wells installed in the basins; one with the wells submerged in water and one with the water already infiltrated, respectively. The bioswales in Bronx Wash were composed of class 1, 2, and 4 topsoil conditions (described in Table 1). These three class types had varying frequencies in stormwater capture with all three classes resulting in 6-8 successful sampling events, depending on the bioswale location. BX TR 25 and BX TR 26 were the most maintained basins of the five bioswales used for this study. This maintenance may be responsible for higher levels of nitrogen found in water samples, likely caused by fertilizer being added the basin by homeowners. BX TR 25, BX TR 26, and BX TR 1 were the basins that consistently captured the most amount of water. These three basins are all located on 1st Avenue, along the east side of the street, spanning an area of about three residential blocks (recall Figure 4).

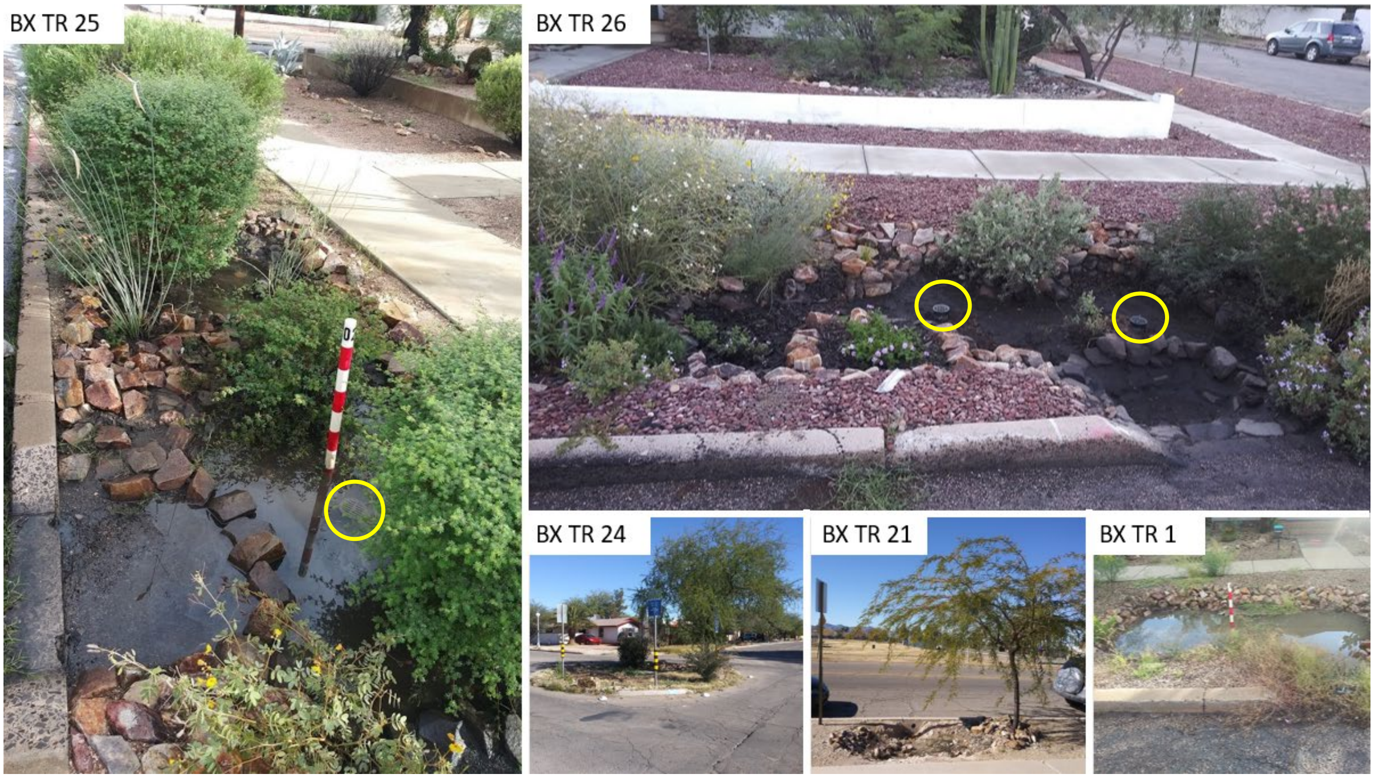

Figure 11. Bronx Wash study sites. Yellow circles indicate the locations of the stilling wells.

Table 3 records the number of times water samples were captured within the water sampling devices and their respective basins. The Y (yes) indicates that water samples were successfully captured, and the N (no) indicates that water samples were not successfully captured. In late February the Feldman's Neighborhood Infrastructure Enhancement Team added a layer of mulch to bioswales BX TR 26 and BX TR 33. This intervened with the sampling process during the rainstorms occurring on 2/22/19 and 3/15/19. After this time period, water samples from these basins were no longer viable.

Table 3. Bronx Wash water capturing device frequency

Storm Event	BX TR 21	BX TR 24	BX TR 26	BX TR 25	BX TR 1	CNTRL
10/1/2018	N	N	N	N	Y	N
10/12/2018	N	N	Y	Y	Y	Y
10/13/2018	N	N	Y	Y	Y	Y
12/7/2018	N	N	Y	Y	Y	Y
12/26/2018	N	N	Y	Y	Y	N

2/5/2019	N	N	Y	Y	N	Y
2/15/2019	N	N	Y	Y	Y	Y
2/22/2019	N	N	Y	-	-	Y
3/15/2019	N	N	Y	-	-	Y
Total Rainfall Capture	**0**	**0**	**8**	**6**	**6**	**7**

The water sampling devices did not capture stormwater runoff in bioswales BX TR 21 and BX TR 24. It should be noted that these bioswales have a significantly different design than the other Bronx bioswales. BX TR 21 has older design with the entrance point consisting of a small circular hole located on the curb (see Figure 12a). This design may have made it difficult for stormwater runoff to run into the bioswale. Moreover, plant and sediment obstructions may have clogged the entrance point. BX TR 24 consists of a roundabout with a large surface area and level ground (see Figure 12b).

Figure 12. a) BX TR 21 has older design with the entrance point consisting of a small circular hole located on the curb. b) BX TR 24 consists of a roundabout with a large surface area and level ground

The stilling wells in High School Wash were not installed until late December 2018. They were not installed at the same time as the Bronx Wash stilling wells because it was unknown how well the devices would function, and the Bronx Wash stilling wells were the test models for this project. After several storms with successful water sampling, which confirmed the structural integrity of the wells in the Bronx bioswales, the project was expanded to include the installation of stilling wells in bioswales in High School Wash. The distribution of the bioswale study sites in High School Wash is more even (see Figure 4). This inconsistency in bioswale distribution between the two study sites adds another level of variability to the analysis, when comparing the effectiveness of the water-capturing devices in both washes.

Figure 13 shows the variety of designs and conditions of the bioswales used in the High School Wash location. The High School Wash bioswales had a different combination of topsoil classifications compared with the Bronx Wash bioswales. HS FT 23, HS TR 2 and HS TR 3 have a fine rock class 5 topsoil composition. HS TR 4 and HS FT 3 have a bare class 4 topsoil composition. HS FT 5 is the only bioswale with a large rock class 2 topsoil composition. The bioswales with class 5 topsoil compositions (HS TR2, HS TR 3 and HS FT 23,) contained water sampling devices that captured water with a frequency of 0%, 25% and 100% respectively. There are many factors, including street elevations, and street pathways that may influence water-capturing frequency that were not analyzed. The basin with the highest frequency of water captured by the water capturing device was HS FT 23 with a topsoil classification of 4.

Figure 13. High School Wash study sites

Table 4 records the number of times water samples were captured within the water sampling devices in High School Wash. Three out of five of the bioswales in Bronx wash captured samples 6-8 times while four out of six bioswales in High School Wash captured samples 1-5 times during the study period.

Table 4. High School Wash water capturing device frequency

Storm Event	HS TR 2	HS TR 3	HS TR 4	HS FT 3	HS FT 5	HS FT 23
12/26/2018	N	N	N	N	Y	Y
2/5/2019	N	N	N	N	Y	N
2/15/2019	N	Y	N	Y	Y	Y
2/22/2019	N	N	N	Y	Y	Y

3/15/2019	N	N	N	Y	Y	Y
Total Rainfall Capture	**0**	**1**	**0**	**3**	**5**	**4**

Figure 14 (see below) includes the water samples from Bronx Wash that were tested for non-purgeable organic carbon (NPOC). These samples were the only ones that were tested because of the limited time available for the research study, and limited funds required to use the Shimadzu machine. The spike in the NPOC, during the December 7 storm event, may be attributed to a long dry period within the basins. For instance, the NPOC levels on October 13 may be lower than the ones on the 12th because the samples were flushed out by the rainfall that occurred on the 12th. This observation is important because the frequency of sample collection, and the frequency of storm events may alter the water quality results in the study site. Therefore, it is important to observe the durations in between storm events when evaluating water quality data.

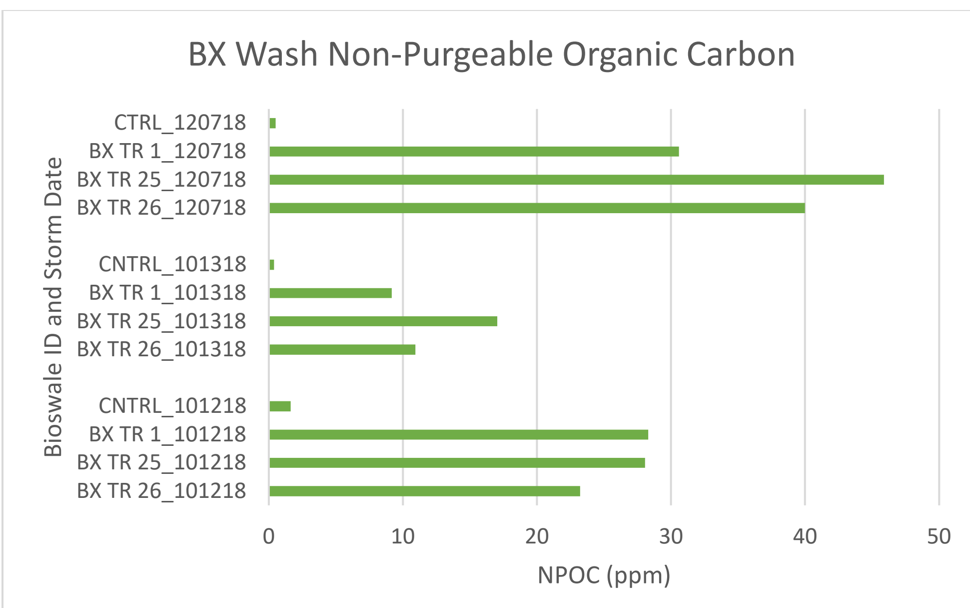

Figure 14. Bronx samples' non-purgeable organic carbon (NPOC) data

Figure 15 includes the water samples from Bronx Wash that were tested for total nitrogen (TN) levels. The results follow a similar pattern observed in Figure 14. For instance, there is a spike in TN during the same storm event that there is a spike in NPOC. There is also a similar decrease in TN between October 12 and October 13.

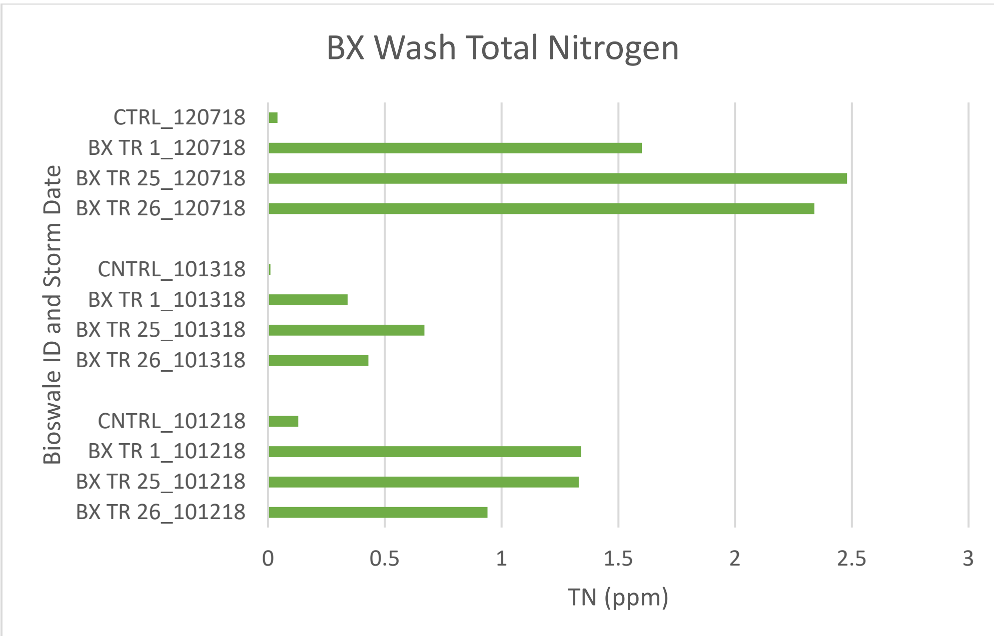

Figure 15. Bronx samples total nitrogen data

Discussion

After staking the wells into the basins there were generally no stability issues. However, we encountered some unanticipated urban problems. Some homeowners modify the basins in front of their homes by watering the basins, planting flowers, and adding fertilizer. Basin BX TR 33 had a new layer of mulch applied, which covered/buried the stilling wells in that bioswale. Water samples were consistently collected from this bioswale, and this intervened with water sampling capabilities and changed the sampling conditions. Adding fertilizer could also cause some unrepresentative results since fertilizer contains high concentrations of nitrogen.

The inconsistencies in qualitative topsoil composition make it difficult to pinpoint why some water-capturing devices captured more water than others. High School Wash had three out of five basins with a class 5 composition while none of the bioswales in Bronx Wash had class 5 compositions. It would have made more sense to select basins that had a narrower scope of topsoil class types to minimize independent variables. However, street connectivity and changes in elevation may be the driving factors in the actual bioswale water retention frequency during storm events.

Future Research

There needs to be a way to resolve the well installation problems. This may require a different stilling well design or installation approach. Furthermore, some basins, including BX TR 21, BX TR 24, HS TR 2, and HS TR 3 did not collect any water during the storms. Since the structural stability of these wells was not the issue, it is likely that stormwater runoff was not favored in these locations, and this defeats the entire point of having basins. Future research could involve on-site observations of stormwater runoff to identify reasons why some bioswales collect water better than others.

The findings in Gallo et al. (2013a) suggest that rainfall depth, the characteristics of the stormwater drainage system, and the variability of solute sourcing due to catchment heterogeneity and above-ground connectivity have the most impact in controlling runoff in the semi-arid study sites located in the Tucson metropolitan area. Therefore, it may be helpful for the wider scope of GI projects in the city to create a stormwater flow model to identify urban flow paths. The US Environmental Protection Agency created a watershed-scale model, SUSTAIN, that can be used to evaluate alternative plans for stormwater runoff quality management and flow abatement techniques in urban and developing areas (Lee et al. 2012). The model requires a comprehensive understanding the main modeling components, including: GIS application; hydrologic/hydraulic and water quality modeling; GI alternatives; and optimizations (Lee et al. 2012). Given the recent and growing GI research being conducted specifically in Tucson, Arizona, it would be interesting to implement the data into the EPA's model to determine the most effective areas to implement GI basins or water capturing devices.

Collecting water quality data at the individual basin scale takes a considerable amount of time and resources. However, since the collection process is relatively easy, and individual well installation is straightforward, it could be beneficial to rely on citizen science for future research. In conclusion, the mini stilling wells successfully filtered out debris, collected the necessary volume of water for water quality analyses, and remained structurally sound despite weather conditions.

References

Anderson, J. H. (2018). Analysis and classification of semi-arid bioswales, (Master's thesis). Retrieved from UA Campus Repository. http://hdl.handle.net/10150/631916

Gallo, E. L., Lohse, K. A., Brooks, P. D., McIntosh, J. C., Meixner, T., & McLain, J. E. (2012). Quantifying the effects of stream channels on storm water quality in a semi-arid urban environment. *Journal of Hydrology*, 470, 98-110.

Gallo, E. L., Brooks, P. D., Lohse, K. A., & McLain, J. E. (2013a). Land cover controls on summer discharge and runoff solution chemistry of semi-arid urban catchments. *Journal of Hydrology*, 485, 37-53

Gallo, E. L., Brooks, P. D., Lohse, K. A., & McLain, J. E. (2013b). Temporal patterns and controls on runoff magnitude and solution chemistry of urban catchments in the semiarid southwestern United States. *Hydrological Processes*, 27(7), 995-1010.

Hale, R. L., Turnbull, L., Earl, S. R., Childers, D. L., & Grimm, N. B. (2015). Stormwater infrastructure controls runoff and dissolved material export from arid urban watersheds. *Ecosystems*, 18(1), 62-75.

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L., & Lai, F. H. (2012). A watershed-scale design optimization model for stormwater best management practices. Environmental Modelling & Software, 37, 6-18.

Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M., & Williams, N. S. (2015). Planning for cooler cities: A framework to prioritize green infrastructure to mitigate high temperatures in urban landscapes. Landscape and urban planning, 134, 127-138.

Purvis, R., Winston, R., Hunt, W., Lipscomb, B., Narayanaswamy, K., McDaniel, A., Lauffer, M., & Libes, S. (2018). Evaluating the water quality benefits of a bioswale in Brunswick County, North Carolina (NC), USA. *Water*, 10(2), 134.

Rockhill, T. K. (2017). Influence of soil physical and chemical properties on soil CO_2 flux in semi-arid green stormwater infrastructure, (Master's thesis). Retrieved from UA Campus Repository.

United States Geological Survey (1999). USGS Circular 1225, The Quality of our Nation's Waters https://www.usgs.gov/special-topic/water-science-school/science/nitrogen-and-water?qt-science_center_objects=0#qt-science_center_objects Accessed April 26, 2019

Wolf, K.L. 2014. Water and Wellness: Green Infrastructure for Health Co-Benefits Stormwater Report, of the Water Environment Federation Management Code. April 2, 2014. https://stormwater.wef.org/2014/04/water-wellness/ Accessed January 22, 2019

Xiao, Q., & McPherson, E. G. (2011). Performance of engineered soil and trees in a parking lot bioswale. *Urban Water Journal*, 8(4), 241-253.