Evaluation of potential for water quality impacts from unlined stormwater basins in the Barton Springs Recharge Zone

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Abstract

The goal of the City of Austin for protection of the Barton Springs Segment of the Edwards Aquifer has been non-degradation of water quality in the aquifer and recharging streams. This has been implemented in the City's jurisdiction by requiring no increase in pollutant loading from new development. Questions have arisen as to the necessity for requiring lined Stormwater Control Measures (SCMs) in the Barton Springs Recharge Zone to meet this non-degradation goal. A comparison of the effluent quality from SCMs to the quality of stormwater runoff from an undeveloped area is used in this report as the gauge of whether infiltration through the use of unlined basins should be allowed. This comparison assumed that effluent quality from the SCMs would be equal to the quality of water that would infiltrate into the subsurface and potentially recharge the aquifer after treatment. Statistical methods consistent with the characteristics of the data were used to make these comparisons. A general linear model using a log-normal distribution was employed to determine if there was a significant difference between undeveloped runoff and SCM effluent for each parameter separately. The results are presented for each paired testing and the significance of differences is provided. The overall conclusion is that no SCM analyzed in this report meets the criteria where every parameter in the effluent has a concentration equal to or less than the concentration in undeveloped stormwater runoff collected by the COA. Therefore it is recommended that further, more targeted study be initiated when possible and no changes be made to current liner requirements until such studies are completed.

Introduction

Infiltration of stormwater through soil is becoming an acceptable strategy in many areas for aquifer recharge and pollutant removal. Distributing runoff to green stormwater infrastructure (GSI) Stormwater Control Measures (SCMs) such as rain gardens is becoming more common as the science of GSI further develops. Any technology that increases infiltration has the potential to return site hydrology to pre-development characteristics with the appropriate capture volume and infiltration design (Brander et al. 2004; Holman-Dodds et al. 2003), restoring the recharge potential of the site in the process. Increasing recharge over background levels may also be obtained by capturing runoff and allowing it to infiltrate through soil to the underlying aquifer in centralized SCMs as well as low impact development (LID) but little is known about the consequences of infiltrating a quantity of water above background levels. In fact, the cumulative value of stormwater infiltration SCMs to increasing aquifer recharge is unknown. GSI methods may have the potential for removal of most stormwater pollutants given adequate soil conditions and vegetation (Neiber et al. 2014).

However, given the sensitivity of the Barton Springs Segment of the Edwards Aquifer, stormwater infiltration directly from the basin or pond portion of SCMs may not be advisable over the Barton Springs Recharge Zone without the treated effluent first passing through the upper most layer of vegetated soil where the majority of biological activity occurs. This would require that the basin or pond portion of any SCM over the Barton Springs Recharge Zone to be lined so that infiltration directly into the subsurface soil could not occur.

Several water quality parameters are increasing over time in the main outlet from the aquifer, Barton Springs (Herrington and Hiers 2010). Some parameters with degrading temporal trends are also commonly elevated in stormwater runoff from development. The increase in pollutants in Barton Springs is at least partially related to uncontrolled non-point source pollution. In addition, drought conditions have contributed to concerns about lower spring discharges and water quality degradation. Drinking water wells drawing from the aquifer have in some cases gone dry or experienced lower quality water (Couch et al. 1997). Regardless of its value to increasing aquifer recharge, increased infiltration of urban runoff may have an unknown cumulative potential to be a water quality problem for both human consumption and endangered species habitat.

The City of Austin has built a long record of monitoring data from stormwater SCMs including some of those that could incorporate infiltration. A comparison of the effluent quality from these SCMs to the quality of stormwater runoff from an undevelolped area is used in this report as the gauge of whether infiltration through the use of unlined basins or ponds would be suitable in the Barton Springs Recharge Zone. To place this analysis in context, a brief review of the relevant regulations and technical literature is provided. Finally, the implications of the analysis results and potential changes to regulations and policy are stated.

Regulatory and Technical Guidance Review

A number of states, counties, cities, and other regulatory entities have liner requirements for SCMs over karst aquifers including the City of Austin (COA) and Texas Commission on Environmental Quality (TCEQ), which govern SCMs over the Barton Springs recharge and contributing zones.

Other Jurisdictions

The City of San Antonio has a good benchmark for regulatory liner requirements over the Southern Edwards Aquifer Recharge Zone. The City of San Antonio Unified Development Code (UDC) Section 35-504 requires, "…adequate measures for the retention, detention and distribution of stormwater in a manner that minimizes the possibility of adverse impacts on both water quantity and water quality during development." However, this section goes on to state that "innovative runoff management practices designed to meet the provisions of the UDC, *enhance the recharge of groundwater*, and maintain the function of critical environmental features are encouraged." But otherwise in Section 35-521, the UDC only specifically requires meeting TCEQ Title 30 of the Texas Administrative Code (TAC) minimum standards for submittal of a Water Pollution Abatement Plan. Therefore, state regulations would apply by reference including sections requiring liners.

The San Antonio River Basin LID Technical Design manual states in Section 2.2.2 that "no retention facilities or pervious pavement without an impermeable liner are allowed over the recharge zone to discourage the infiltration of pollutants." However, this section goes on to say that "although this limitation must be understood prior to site assessment *for infiltration BMPs in the recharge zone*, LID BMPs can be adapted for use in all Edwards Aquifer Zones" (Dorman et al. 2013).

The Northern Tennessee Water Quality SCM Manual indicates that in "areas with karst topography" water quality basins are required to have a liner. This is necessary to "sustain a permanent pool of water and protect aquifers."

In the Chesapeake Bay, stormwater guidelines for karst terrain are provided for reference or adoption in local and state land development codes, ordinances, regulations, permits and engineering manuals by the Chesapeake Stormwater Network. Guidance here is that a "minimum of 50% of the total water quality volume must be treated by a filtering or bioretention practice *prior to any infiltration*." However, in areas of particular sensitivity, *infiltration is strictly prohibited*. Basin types that are specifically mentioned as needing liners include extended detention, constructed wetlands, and wet ponds. The use of centralized stormwater practices with large drainage areas is strongly discouraged even when liners are used.

In the St. Johns River Water Management District in Florida, rules for stormwater basins in karst areas provide minimum measures that include the requirement for fully vegetated basin side slopes and bottoms and at least three feet of unconsolidated soil material between the surface of the limestone bedrock and the bottom and sides of the stormwater basin. In sensitive areas, additional requirements may be imposed depending on the potential for contamination to the Floridan Aquifer including either clay or geotextile basin liners.

City of Austin Regulations

COA protects the water quality and quantity of Barton Springs and the Edwards Aquifer through the Land Development Code (LDC), Save our Springs (SOS) ordinance, and Environmental Criteria Manual (ECM) Section 1.6.9 design guidance. LDC section 25-8-213 (A)(2) states that throughout the COA "An impervious liner is required in an area where there is surface runoff to groundwater conductivity. " This goes on to say that "iIf a liner is required and controls are located in series, liners are not required for the second or later in the series following sedimentation, extended detention, or sedimentation/filtration." This would presumably cover irrigation fields, biofiltration basins, and infiltration fields if following primary treatment in an SCM series.

The SOS ordinance in LDC section 25-8-514 (A) specifically states that "runoff from such development (covered by SOS) shall be managed through water quality controls and onsite pollution prevention and assimilation techniques so that no increases occur in the respective average annual loadings of total suspended solids, total phosphorus, total nitrogen, chemical oxygen demand, total lead, cadmium, *Escherichia coli*, volatile organic compounds, total organic carbon, pesticides, and herbicides from the site." Therefore in practice, SCMs must meet the strict requirement that developed loads must be equal to or less than the loads in runoff from the existing, typically undeveloped, site. This has been interpreted to prohibit unlined stormwater treatment basins over the Barton Springs Recharge Zone (BSRZ). Specifically, basin liner requirements are provided in ECM 1.6.2(C), ECM 1.6.5(D)(3), and ECM 1.6.7(A).

Additionally, throughout the city, infiltration is prohibited in areas at high risk of contamination due to land use or environmental features. Examples include rain gardens "where infiltration would cause or contribute to...contamination in soil or groundwater" (ECM 1.6.7(H)) and porous pavement "under stormwater hot spots" (ECM 1.6.7(E)). Even in locations within the Barton Springs Zone where irrigation is used without a liner (as a second water quality control in series), a minimum depth of "12 inches of native or enhanced soil" must be provided beneath the irrigation area (ECM 1.6.7(A)).

ECM 1.6.9.3 states that "For stormwater control measures that do not discharge directly to the surface drainage system (i.e. infiltration measures), the proposed treatment methodology shall be designed to meet the pollutant loading reduction requirements for runoff prior to the treated runoff's re-emergence to the surface or entering the local groundwater system." Unlined basins, permeable friction course (PFC), and infiltration/irrigation fields could be interpreted to be adequate anywhere the treated effluent would meet the quality of runoff (or recharge) from an undeveloped site. Likewise, overland flow section 25-8-185(A)(2) specifies that in all areas of Austin, drainage patterns on a site *must maintain infiltration and recharge of local seeps and springs*. Presumably, SCMs discharging from a pipe to surface water directly would not be preferred over those that contribute to the maintenance of recharge to springs and seeps. Outside the BSRZ, infiltration is encouraged and methods of determining infiltration rates for selecting water quality controls are provided in ECM Section 1.6.7.4. Therefore, an assessment of whether large scale centralized water quality controls can be unlined in the BSRZ if they meet SOS standards is reasonable.

State of Texas Regulations

State regulations in 30 TAC 213 (a) were written with the specific purpose to "regulate activities having the potential for polluting the Edwards Aquifer and hydrologically connected surface streams in order to *protect existing and potential uses of groundwater* and maintain Texas Surface Water Quality Standards." No mention of liner requirements is made in the regulation itself. If hydrologically connected surface streams experienced pollutant concentrations at undeveloped background levels from stormwater runoff and the infiltration resulting from the SCMs is of no worse quality, then unlined stormwater basins should be permissible under this TCEQ rule. TCEQ Technical Guidance on SCMs (RG-348) implementing these regulations definitively requires impermeable liners for permanent structural best management practices in section 3.2.7 for wet ponds and in 3.4.2 for retention, extended detention, sand filters, and constructed wetlands. "Concrete, clay, or geomembrane may be used" and TCEQ references engineering properties for each of these types of liners from the COA ECM 1.6.2(C) (Barrett 2005). In contrast, this guidance also mentions that "the use of check dams with swales also promotes infiltration" as a potential benefit of (unlined) swales (Pratt 2004).

Impermeable liners are commonly required for stormwater basins in karst recharge areas. In some cases, exceptions are made for small-scale LID and GSI SCMs where adequate soil and vegetation reduce the threat to groundwater quality. Since conflicting guidance exists regarding liner requirements for small-scale SCMs, the question of whether requirements should be relaxed in karst recharge zones warrants a detailed examination.

Literature Review

Monitoring studies of stormwater infiltration which include groundwater impacts and hydrologic characterization were included in this section, in addition to modeling studies of runoff, infiltration, and groundwater quality.

Monitoring Literature

Monitoring studies of groundwater impacts from stormwater are abundant, but few are specific to infiltration impacts from SCMs on karst aquifers and no studies were found that specifically compare lined to unlined systems. Effluent quality from SCMs has also been studied extensively; but use of local data when available (as is the case in Austin) is preferable to making regulatory and design decisions based on literature alone. References for COA SCM data and analysis can be found in COA (2013a) and COA (2013b). Data from small watersheds as influent to SCMs can be found in COA (2009).

The main forms of treatment in infiltration systems are sorption, precipitation, trapping, straining and bacterial degradation upon movement through the soil. These treatment mechanisms are usually only appropriate where the soil is of high/moderate permeability, the groundwater is at least three meters below the infiltration point, there is sufficient storage capacity to allow infiltration, and the suspended solids concentration of the runoff is low to prevent blockages of the systems (Bruen et al. 2006).

A literature review on sustainable drainage management methods provided several references for application of infiltration in Europe, primarily in the UK. Despite the extensive use of infiltration systems, there has been limited examination of their performance. There has also been widespread concern regarding the hydraulic performance of the systems, with the general expectation that failure through blockage by sediment and debris would necessitate reconstruction within a limited time span (Pratt 2004). Pratt (2004) also noted that at the time of his literature review, there was growing concern about the impact to groundwater from the infiltration system effluent.

Wanielista and Hulstein (2006) looked at irrigation SCMs and nitrate breakthrough in groundwater. The conclusion was made that irrigating with stormwater with a nitrate nitrogen concentration of up to 2 mg/L had very little effect on the groundwater nitrate content at a depth of four feet; the removal efficiency was determined to be about 97 percent.

In Florida, the Department of Environmental Protection has conducted research on nitrogen transport beneath stormwater retention basins. As with Barton Springs, nitrogen levels in some springs in Florida have been steadily increasing over time, which has had an impact on the economy of the region. Two unlined stormwater infiltration basins using different soil types were monitored for a number of water quality parameters in soil, basin water, soil gas, soil water, and shallow groundwater media. Suction lysimeters were installed at multiple depths up to 1.4 m and monitoring wells were sampled for shallow and deep groundwater. The basin with soil at a lower rate of hydraulic conductivity was found to remove nitrogen in the vadose zone before it entered the deeper groundwater flow system while a second basin with higher hydraulic conductivity was unsuccessful in nitrogen removal. Results were also found to vary with season, summer samples showing better nitrogen removal than fall or winter. Recommendations from the report included use of soil augmentation with an engineered Biosorption Activated Media (BAM) composed from a 1.0:1.9:4.1 mixture (by volume) of tire crumb, silt and clay, and sand to improve treatment (Wanielista et al. 2011).

Hydrology

A well referenced literature review of LID and centralized stormwater infiltration SCMs was provided by Purdue University researchers. The review consistently found that processes such as infiltration and evapotranspiration play an important role in runoff retention in LID (Ahiablame et al. 2012). One study of bioretention (Chapman and Horner 2010) showed that 48 % to 74 % of runoff that flows through bioretention systems escapes in the form of infiltration and evaporation. Another study showed that 20 % to 50 % through similar processes (Li et al. 2009). This study period, however, was rather limited at less than 5 months.

The results of another study showed that the long-term behavior of the infiltration capacity relies largely on the type and age of the system, and when the age of the system was over nine years, grass-lined infiltration SCMs had the lowest infiltration capacity of those tested (Al-Rubaei et al. 2013). The main threat to the long-term hydraulic performance of stormwater infiltration systems is their tendency to become clogged due to accumulated sediment deposits on the system surface (Dietz 2007). After years of operation, measured infiltration capacities were far below the initial values as compared to the reference site (Al-Rubaei et al. 2013). These results suggest that infiltration SCMs would not necessarily result in long term recharge benefits if implemented in the BSRZ without proper maintenance.

Modeling

The Purdue review discussed above includes literature on modeling LID performance of various types of SCMs. The review indicates that "simulation modeling provides valuable insight to extrapolate this information to different spatial (field to watershed) and temporal (single event to long-term simulations) scales" (Ahiablame et al. 2012) and extends the limited monitoring data.

As a relatively new suite of SCMs, LID has not been studied as much as conventional stormwater treatment. Models of such systems for routine planning and design are under development but not standardized. The widespread adoption of an accurate model to give proper credit to LID components is critical for widespread adoption of LID techniques (Dietz 2007).

Clark and Pitt (2007) presented a case for infiltration based on concentration of influent and effluent, soil properties, and pretreatment levels of SCMs such that groundwater would be protected. The article provides a detailed literature review of the performance of various SCMs. The paper also outlines an evaluation method that employs water quantity and quality models to determine the benefits and deficits of infiltration SCMs. These range from a simple mobility, abundance, and solubility categorization model to an application of SESOIL (Seasonal Soil compartment model), which uses mass balances and assumes phase equilibrium to calculate the fate and transport of inorganic and organic pollutants. Scenarios for modeling were provided but no subsurface data was used for calibration. Therefore, it could not be determined how discharges of pollutants to groundwater compared to background levels. The conclusion of the study was that surface infiltration devices such as soil and vegetation based infiltration SCMs, and porous pavement had more potential for pollutant control than subsurface infiltration SCMs such as wells, French drains, infiltration pits, and percolating pipe. This would indicate that subsurface SCMs should not be used in sensitive environments as the BSRZ unless significant pretreatment is provided to achieve background pollutant levels.

This brief review is only a small subset of the technical literature available. Regardless, based on the literature reviewed, no definite conclusion can be drawn as to the ability of unlined SCMs to meet SOS standards for infiltrated stormwater. More evidence was found for the ability of some SCMs to attenuate floods, restore natural hydrology, and recharge groundwater. Less evidence was found for the treatment to consistently attenuate pollutant concentrations in groundwater to those of undeveloped runoff. This is especially true for those SCMs situated over karst aquifers. Very few studies evaluated centralized SCMs without liners over karst aquifers because, as noted above, regulations in most areas of karst areas require lined SCMs. More data is needed to support allowing stormwater infiltration via unlined SCMs in the BSRZ.

Methods

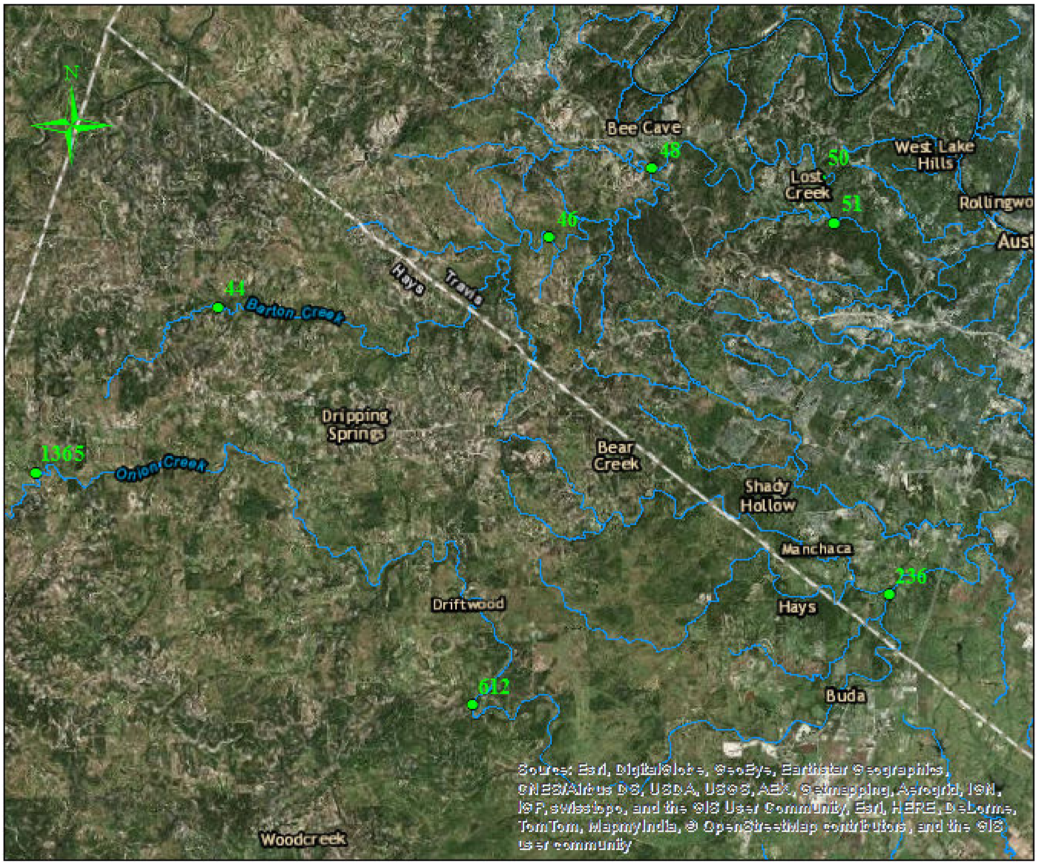
Data collected in Austin, TX, was aggregated into a meta-analysis comparison of water quality parameters. Samples were taken from streams under baseflow conditions, stormwater runoff from undeveloped locations, and various SCM effluents including permeable friction course (PFC), sand filter, bio-filtration, and retention-irrigation (collected after retention basin treatment but before application to the irrigation field) effluent. Effluent quality analyzed from each SCM is equivalent to the quality of water that would be infiltrated into the subsurface after treatment from each SCM if unlined basins were allowed. Parameters used in the analysis include chemical oxygen demand (COD), total suspended solids (TSS), zinc, *E. coli,* total organic carbon (TOC), nitrate, total nitrogen, dissolved phosphorus, and total phosphorus. With the exception of nitrate and dissolved phosphorus, the above parameters, in addition to lead, are listed as water quality pollutants of concern for the Barton Springs Zone in the COA LDC and all development within the Barton Springs Zone must demonstrate non-degradation (based on average annual loading) based on these parameters (LDC Chapter 25-8 Article 13). Nitrate and dissolved phosphorus are included because they are forms of nitrogen and phosphorus available for biological uptake and can lead to eutrophication of surface waters if present in excess concentrations. Lead concentrations were not analyzed because it was thought that historical data, impacted from leaded gasoline, could skew inferences about current concentrations of lead.

Baseflow data used in the analysis was collected by the COA from 1994 to 2010 in the mainstem of recharging streams within the Barton Spring Zone with less than 10% cumulative impervious cover at the site location (Table 1, Figure 1). This data is most representative of recharge into the aquifer through the bottom of creeks during non-storm influenced conditions. Water samples were collected following procedures and baseflow conditions defined by the Water Resource Evaluation Standard Operating Procedure Manual (COA 2012).

Table 1: Site number, site name, longitude, and latitude for locations of baseflow data.

Site #	Site Name	Longitude	Latitude
44	Barton Creek at Stark Pool	-98.12569	30.24492
46	Barton Creek at Shield Ranch Pool	-97.97351	30.26979
48	Barton Creek at Hwy 71 ds Little Barton Creek	-97.92609	30.29623
50	Barton Creek at Leif Johnson Pool	-97.84925	30.29136
51	Barton Creek ds Lost Creek Blvd	-97.84323	30.27307
236	Onion Creek at Twin Creeks Rd	-97.82225	30.12546
612	Onion Creek near Driftwood (Hwy 150)	-98.01337	30.08543
1365	Onion Creek at Pfulman Ranch	-98.21038	30.18070

Undeveloped stormwater runoff was noted in this report as either “Undeveloped Runoff USGS” or “Undeveloped Runoff COA.” The Undeveloped Runoff USGS values were collected through a cooperative monitoring agreement with the United States Geological Survey (USGS) from gages located in the mainstem of creeks with minimal development. Undeveloped Runoff COA values were collected from surface water runoff in undeveloped upland areas with smaller drainage areas by the COA. Undeveloped COA values are representative of runoff that would infiltrate through soils over the recharge zone or flow directly into the aquifer via upland recharge features (e.g., caves, sinkholes) outside of the active creek channel. Undeveloped USGS values are representative of stormwater recharge to the aquifer through creeks over the recharge zone.



Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, Esri, HERE, DeLorme, TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 1: Map locations where baseflow date was collected.

Permeable friction course (PFC) is a type of porous pavement that is applied over an impervious concrete or conventional asphalt base. Fully porous pavements are sometimes used in parking lots, driveways, and sidewalks to reduce runoff volume; however, fully porous pavements are applied on pervious material while a PFC is applied over an impervious base. The interconnected voids in the overlay of PFC allow rainwater to drain down into the pavement and then flow over the impervious base to the edge of the pavement. Studies have shown that porous asphalt overlays may reduce the concentrations of pollutants in stormwater runoff (Barrett and Shaw 2007; Berbee et al. 1999).

Sand filters are structural SCMs that capture and temporarily store stormwater runoff and filter the runoff through a bed of sand. A typical Austin sand filter has two basic components: the pretreatment sedimentation basin and the sand filter basin. The sedimentation basin reduces the amount of sediment that reaches the sand filter and in some cases helps stormwater reach the sand filter as sheet flow. The sand filter traps the finer sediment and sediment-bound pollutants and may provide a media for microbial removal of bacteria. The filtered runoff is collected by an underdrain and discharged to a creek or storm sewer.

Biofiltration uses the chemical, biological, and physical properties of plants, microbes, and soils for removal of pollutants from stormwater runoff. The COA design of biofiltration system is similar to a sand filter except the filtration media is biologically active and can support plant growth. The primary difference between sand filtration and biofiltration is that the presence of a biological community of plants and microorganisms in a biofiltration system can theoretically provide more treatment of runoff, especially nitrates which are problematic in sand filters.

Retention-irrigation systems consist of three main components: a retention basin, an irrigation system, and an irrigation field. The retention basin collects and holds runoff from the area to be treated up to a given design volume based on the drainage area, impervious cover, and the 2-year, 3-hour rainfall event in the Austin area. Excess volumes are allowed to bypass the pond untreated. The irrigation portion should be designed to deliver the volume of the retention basin uniformly to the irrigation field over a set time. Current rules require the full retention basin volume to be emptied within 72 hours after the rain ends with no irrigation during the first 12 hours, unless the system is gravity drained. In addition, the irrigation cannot be continuous but must alternate application and rest periods. The irrigation field is used for treated runoff infiltration rather than runoff being discharged into a waterway. Data for retention-irrigation systems in this report was collected prior to the water being filtered through the irrigation field.

Locations of sand filter systems, retention-irrigation systems, and undeveloped runoff collection sites along with sampling methods for all SCMs presented in this report, with the exception of PFC, can be viewed in previous COA reports (COA 2009, 2013a, 2013b). Locations and sampling methods associated with PFC controls are available in Eck et al. (2012). Data representing biofiltration effluent was collected from two raingardens draining the parking lot of One Texas Center located at 505 Barton Springs Road, Austin, TX, and one additional biofiltration system located within Gillis Park on South First Street. Additional SCM information can be found in the COA Environmental Criteria Manual.

Data Analysis

A general linear model was used to determine if there was a significant difference between runoff types for each parameter separately. Continuous parameters (all except *E. coli*) were modeled using a lognormal distribution. A lognormal distribution is described as a distribution which will lead to a normal distribution if the logarithm of the parameter is computed, and is a common distribution in environmental parameters. If a parameter is continuous with a positive distribution and a long tail then a lognormal distribution can be used to fit the data and will lead to better parameter estimates when compared to a normal distribution (McGill et al. 2006). *E. coli* is a discrete parameter and was initially modeled using a Poisson distribution; however, overdispersion, more variation in the data than in the model, was noted and the negative binomial distribution was used instead to account for the variation.

Models were computed using the PROC GLIMMIX procedure in SAS version 9.2 and back transformations of the mean and standard errors were computed according to SAS 9.2 User's Guide formulas:

$$E[Y] = \exp\{\mu\}\sqrt{\varpi}$$

$$Var[Y] = \exp\{2\mu\}\,\varpi(\varpi - 1)$$

$$\varpi = \exp\{\sigma^2\}$$

Where σ is the standard error of the lognormal model, μ is the mean of the lognormal model, E[Y] is the mean of the back transformed model, and the square root of Var[Y] is the standard error of the back transformed model.

Multiple comparison tests were done to obtain information about differences among the means using the LSMEANS option in the PROC GLIMMIX procedure. The simplest method to compare means is to directly compare every pair of means using a *t* test. Two means are considered different if the *t* value computed between the two means is greater than or equal to $t(\alpha; \boldsymbol{\nu})$, a two-tailed critical value from the Student's *t* distribution where α is the significance level and $\boldsymbol{\nu}$ is the number of degrees of freedom. When multiple *t* tests are used in conjunction, the experiment-wise type one error rate becomes much higher than the desired significance value of 0.05. To correct the experiment-wise error rate, the two-tailed critical value from the Student's *t* distribution for each pairwise comparison was set to $t(\varepsilon; \boldsymbol{\nu})$ via a Bonferroni adjustment (Miller 1981):

$$\varepsilon = \frac{2\alpha}{k(k-1)}$$

where *k* is the total number of means being compared.

Results

Chemical Oxygen Demand (COD)

The mean, standard error, and 95% confidence interval for COD in baseflow, biofiltration effluent, PFC effluent, retention-irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 2. The concentration of COD in baseflow was significantly lower than in any other runoff type. Concentrations of COD in the undeveloped runoff collected by the COA was significantly less than COD concentrations in PFC effluent, significantly higher than concentrations in sand filter effluent, and not different from concentrations in retention-irrigation effluent or undeveloped runoff collected from the USGS (Figure 2). A full list of differences between runoff types and associated p-values for every parameter can be seen in Appendix A.

Table 2: Mean, standard error, and 95% confidence interval for chemical oxygen demand (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Significantly Different
Baseflow	6.05	0.37	5.35	6.83	All
Biofiltration	28.70	2.40	24.37	33.81	Baseflow, PFC, Sand Filter, Undeveloped Runoff USGS
PFC	47.56	3.80	40.67	55.62	All
Retention Irrigation	24.20	2.02	20.55	28.51	Baseflow, PFC
Sand Filter	18.71	1.27	16.38	21.37	Baseflow, Biofiltration, PFC, Undeveloped Runoff COA
Undeveloped Runoff COA	25.37	1.59	22.44	28.68	Baseflow, PFC, Sand Filter
Undeveloped Runoff USGS	18.80	1.65	15.83	22.33	Baseflow, Biofiltration, PFC

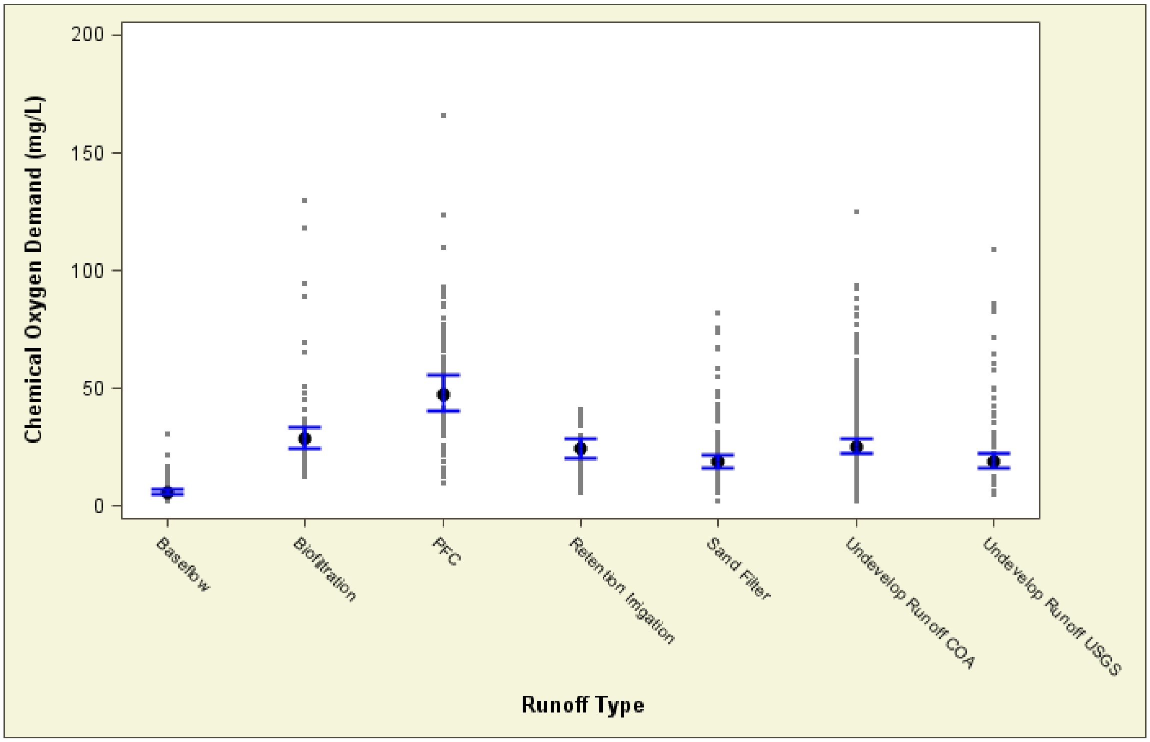


Figure 2: Chemical oxygen demand (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Total Suspended Solids (TSS)

The mean, standard error, and 95% confidence interval for TSS in baseflow, biofiltration effluent, PFC effluent, retention irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 3. The concentration of TSS in baseflow was significantly lower than in any other runoff type. TSS concentrations in undeveloped runoff collected by the COA were significantly higher than any effluent type in addition to baseflow concentrations, but concentrations in undeveloped runoff collected by the COA were significantly lower than in undeveloped runoff collected by the USGS (Figure 3).

Table 3: Mean, standard error, and 95% confidence interval for total suspended solids (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	1.18	0.07	1.06	1.32	All
Biofiltration	6.42	1.01	4.72	8.73	Baseflow, Retention Irrigation, Undeveloped Runoff COA, Undeveloped Runoff USGS
PFC	8.49	1.26	6.36	11.34	Baseflow, Undevelop Runoff COA, Undeveloped Runoff USGS
Retention Irrigation	13.11	2.05	9.66	17.78	Baseflow, Biofiltration, Undeveloped Runoff COA, Undeveloped Runoff USGS
Sand Filter	11.38	1.45	8.87	14.60	Baseflow, Undeveloped Runoff COA, Undeveloped Runoff USGS
Undeveloped Runoff COA	30.91	3.59	24.62	38.80	All
Undeveloped Runoff USGS	74.41	11.11	55.59	99.59	All

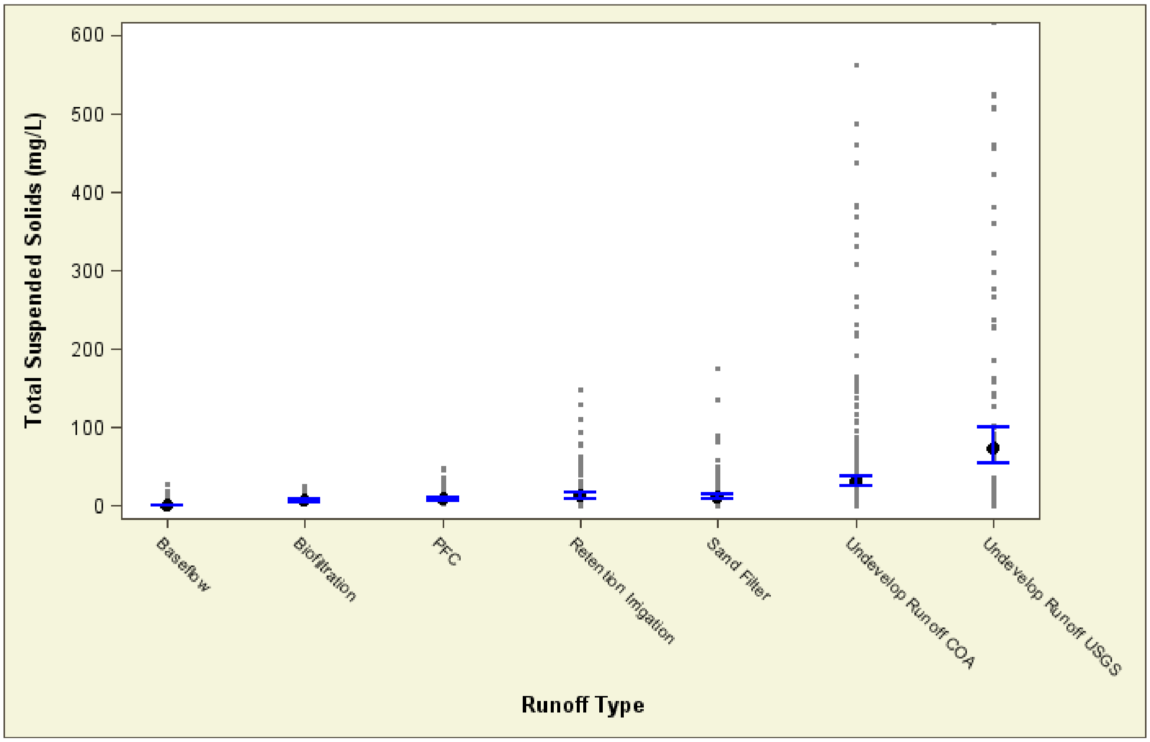


Figure 3: Total suspended solids (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Zinc

The mean, standard error, and 95% confidence interval for zinc in baseflow, biofiltration effluent, PFC effluent, retention-irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 4. The concentrations of zinc in baseflow and biofiltration effluent were significantly lower than in any other runoff type (Figure 4). Zinc concentrations in the undeveloped runoff collected by the COA were only significantly lower than zinc concentrations collected in PFC effluent.

Table 4: Mean, standard error, and 95% confidence interval for zinc (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	5.45	0.71	4.23	7.02	PFC, Retention Irrigation, Sand Filter, Undeveloped Runoff COA, Undeveloped Runoff USGS
Biofiltration	3.15	0.43	2.41	4.12	PFC, Retention Irrigation, Sand Filter, Undeveloped Runoff COA, Undeveloped Runoff USGS
PFC	22.00	2.86	17.06	28.37	Baseflow, Biofiltration, Retention Irrigation, Undeveloped Runoff COA, Undeveloped Runoff USGS
Retention Irrigation	11.97	1.64	9.16	15.65	Baseflow, Biofiltration, PFC
Sand Filter	18.64	2.10	14.94	23.24	Baseflow, Biofiltration
Undeveloped Runoff COA	11.94	1.22	9.78	14.58	Baseflow, Biofiltration, PFC
Undeveloped Runoff USGS	11.34	1.94	8.12	15.85	Baseflow, Biofiltration, PFC

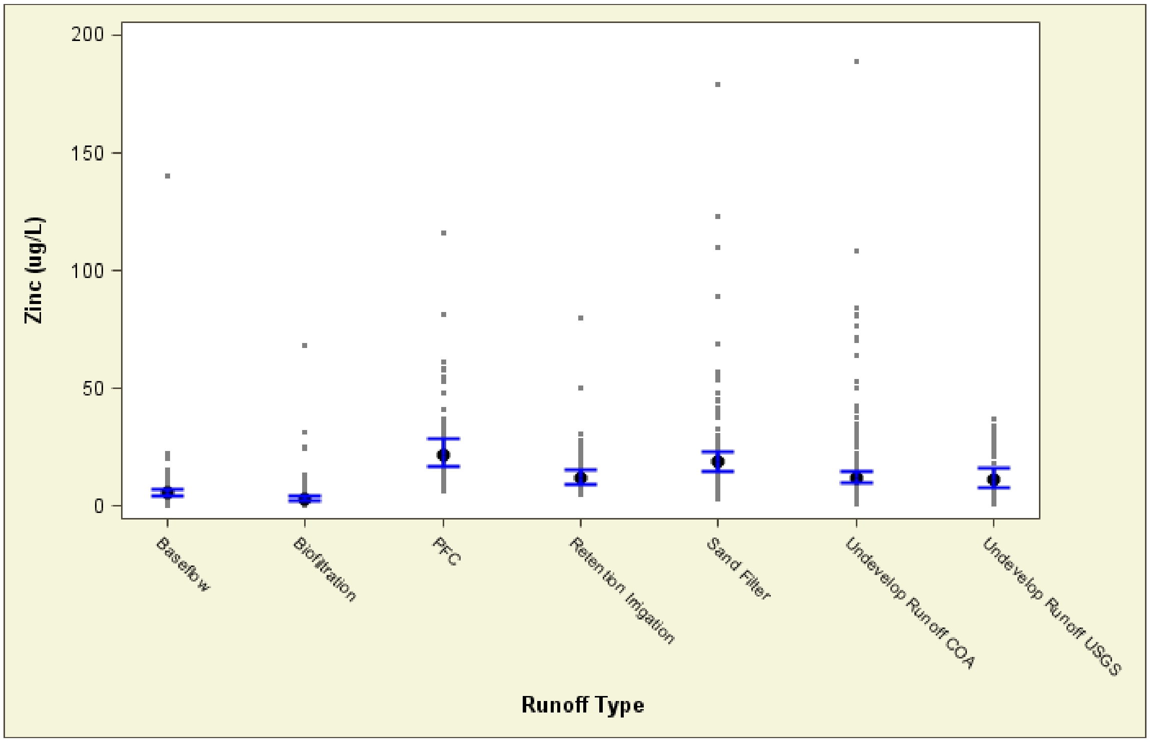


Figure 4: Zinc (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Escherichia coli

E. coli data is the count of bacteria colonies in a given volume of water, and is used as a surrogate for fecal contamination. Count data has inherent properties that make it distinguishable from continuous data and should be modeled differently. Thus *E. coli* was modeled using a negative binomial distribution instead of a lognormal distribution. The negative binomial distribution was used instead of the Poisson distribution due to a large amount of overdispersion, more variation in the data when compared to the model, using a Poisson distribution. Limited *E. coli* data was present in certain runoff types. The mean, standard error, and 95% confidence interval for *E. coli* in baseflow, biofiltration effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 5. *E. coli* in undeveloped runoff collected by the COA was significantly higher than *E. coli* in baseflow conditions or biofiltration effluent (Figure 5).

Table 5: Mean, standard error, and 95% confidence interval for *E. coli* (MPN/100 mL) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	75	5	65	85	All
Biofiltration	1104	560	407	2993	All
Sand Filter	5312	678	4134	6827	Baseflow, Biofiltration
Undeveloped Runoff COA	6892	1027	5143	9236	Baseflow, Biofiltration
Undeveloped Runoff USGS	5674	939	4099	7855	Baseflow, Biofiltration

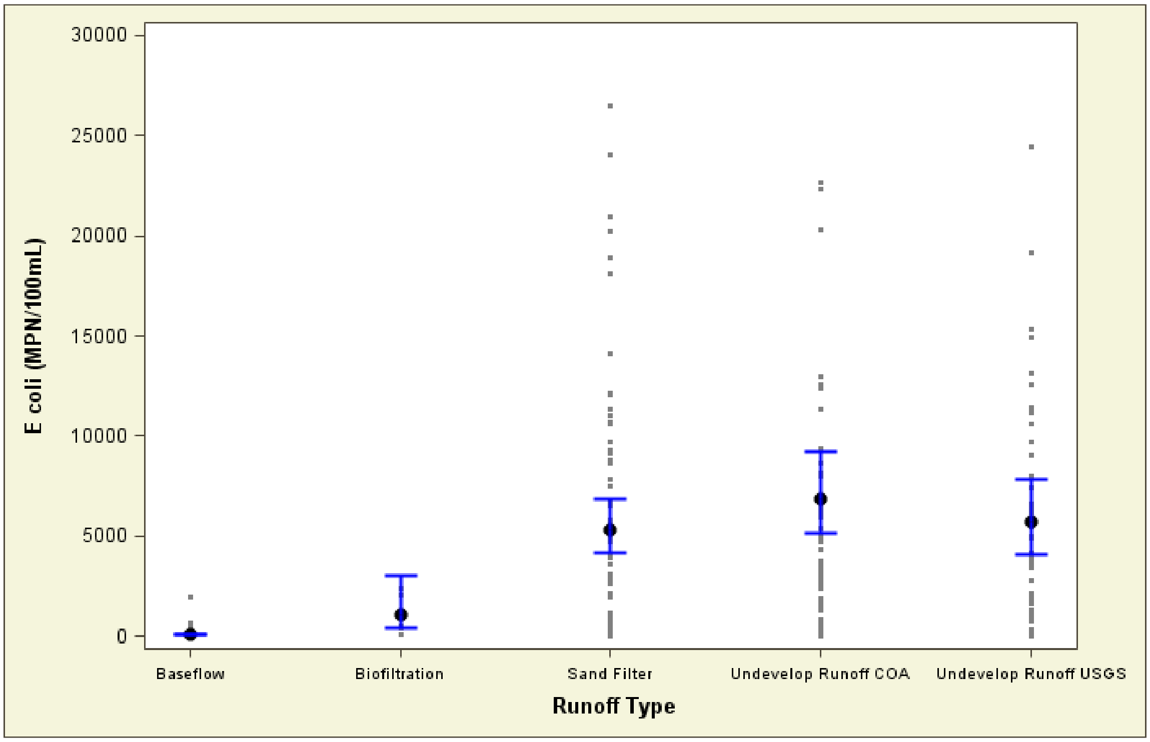


Figure 5: *Escherichia coli* (MPN/100 mL) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Total Organic Carbon (TOC)

The mean, standard error, and 95% confidence interval for TOC in biofiltration effluent, retention-irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 6. Concentrations of TOC were significantly lower in sand filter effluent when compared to any other runoff type and no other significant difference existed between analyzed runoff types (Figure 6).

Table 6: Mean, standard error, and 95% confidence interval for total organic carbon (mg/L) from samples collected from stormwater runoff from undeveloped land and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Biofiltration	7.99	0.65	6.81	9.37	Sand Filter
Retention Irrigation	8.73	0.71	7.44	10.24	Sand Filter
Sand Filter	5.90	0.41	5.15	6.76	All
Undeveloped Runoff COA	8.38	0.51	7.43	9.45	Sand Filter
Undeveloped Runoff USGS	9.09	0.71	7.80	10.60	Sand Filter

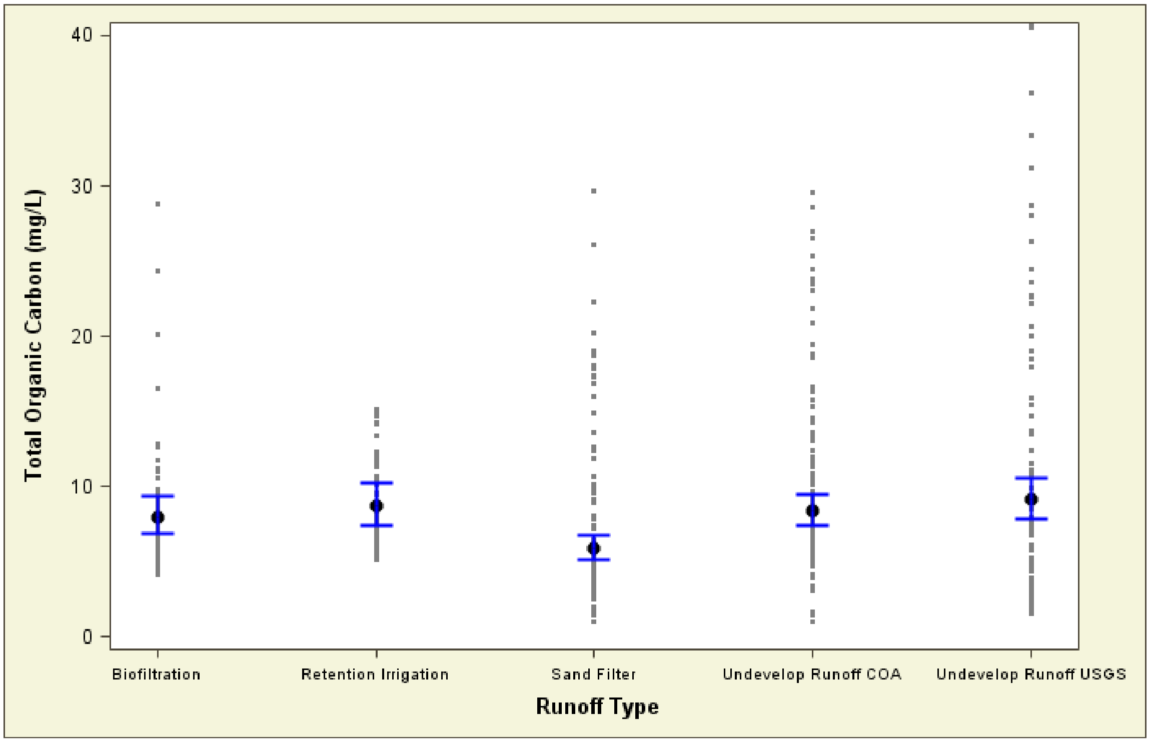


Figure 6: Total organic carbon (mg/L) from samples collected from the stormwater runoff from undeveloped land and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Nitrate

The mean, standard error, and 95% confidence interval for nitrate in baseflow, biofiltration effluent, retention irrigation-effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 7. Concentrations of nitrate in baseflow are significantly lower than in all other runoff types. Nitrate concentrations in undeveloped runoff collected by the COA were significantly lower than concentrations in sand filter effluent but were not different from concentrations in biofiltration or retention-irrigation effluent (Figure 7).

Table 7: Mean, standard error, and 95% confidence interval for nitrate (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was set at 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	0.07	0.003	0.06	0.07	All
Biofiltration	0.38	0.055	0.28	0.50	Baseflow, Retention Irrigation, Undeveloped Runoff USGS
Retention Irrigation	0.18	0.026	0.13	0.23	Baseflow, Biofiltration, Sand Filter
Sand Filter	0.53	0.063	0.42	0.67	Baseflow, Retention Irrigation, UndevelopedRunoff COA, Undevelop Runoff USGS
Undeveloped Runoff COA	0.25	0.027	0.20	0.31	Baseflow, Sand Filter, Undeveloped Runoff USGS
Undeveloped Runoff USGS	0.14	0.020	0.11	0.18	Baseflow, Biofiltration, Sand Filter, Undeveloped Runoff USGS

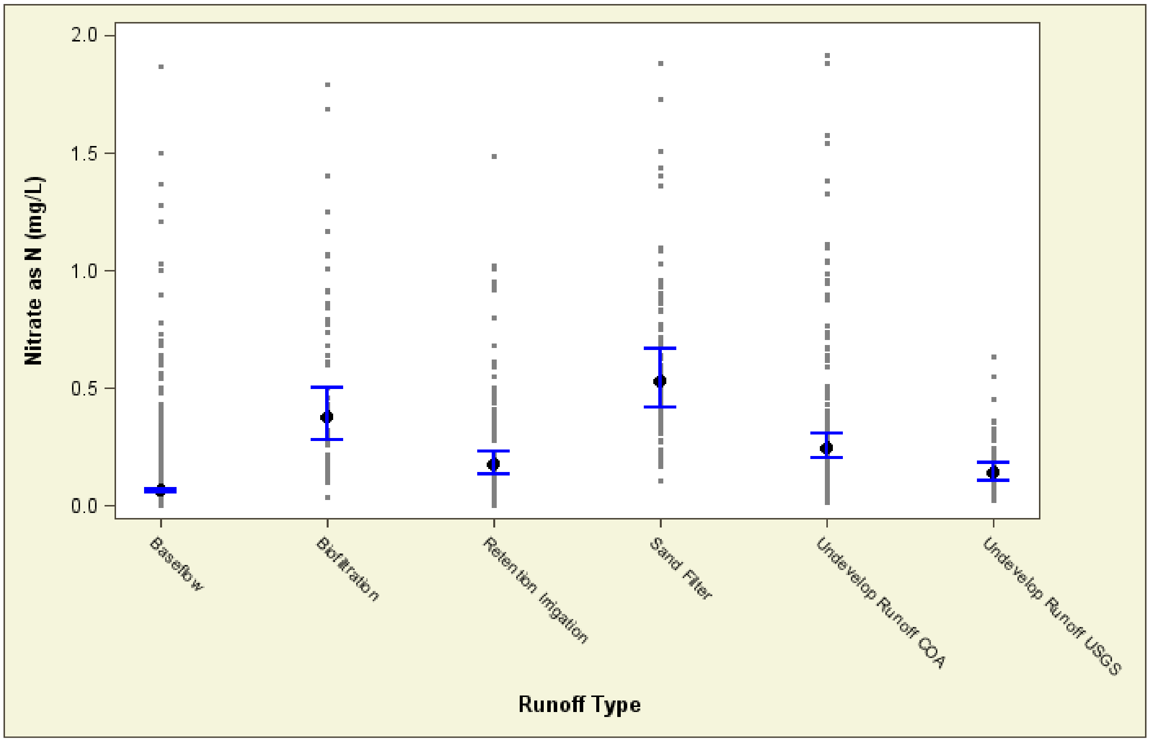


Figure 7: Nitrate (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Total Nitrogen

The mean, standard error, and 95% confidence interval for total nitrogen in baseflow, biofiltration effluent, PFC effluent, retention irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 8. Concentrations of total nitrogen in baseflow are significantly lower than in all other runoff types. Concentrations in undeveloped runoff collected from the COA were not significantly different from other forms of runoff or effluent, only higher than the baseflow concentrations previously mentioned (Figure 8).

Table 8: Mean, standard error, and 95% confidence interval for total nitrogen (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was set at 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	0.25	0.01	0.23	0.27	All
Biofiltration	1.17	0.10	0.99	1.38	Baseflow, Undeveloped Runoff USGS
PFC	1.04	0.08	0.89	1.22	Baseflow
Retention Irrigation	1.05	0.09	0.89	1.24	Baseflow
Sand Filter	0.96	0.07	0.84	1.10	Baseflow
Undeveloped Runoff COA	0.89	0.06	0.79	1.01	Baseflow
Undeveloped Runoff USGS	0.79	0.06	0.68	0.93	Baseflow, Biofiltration

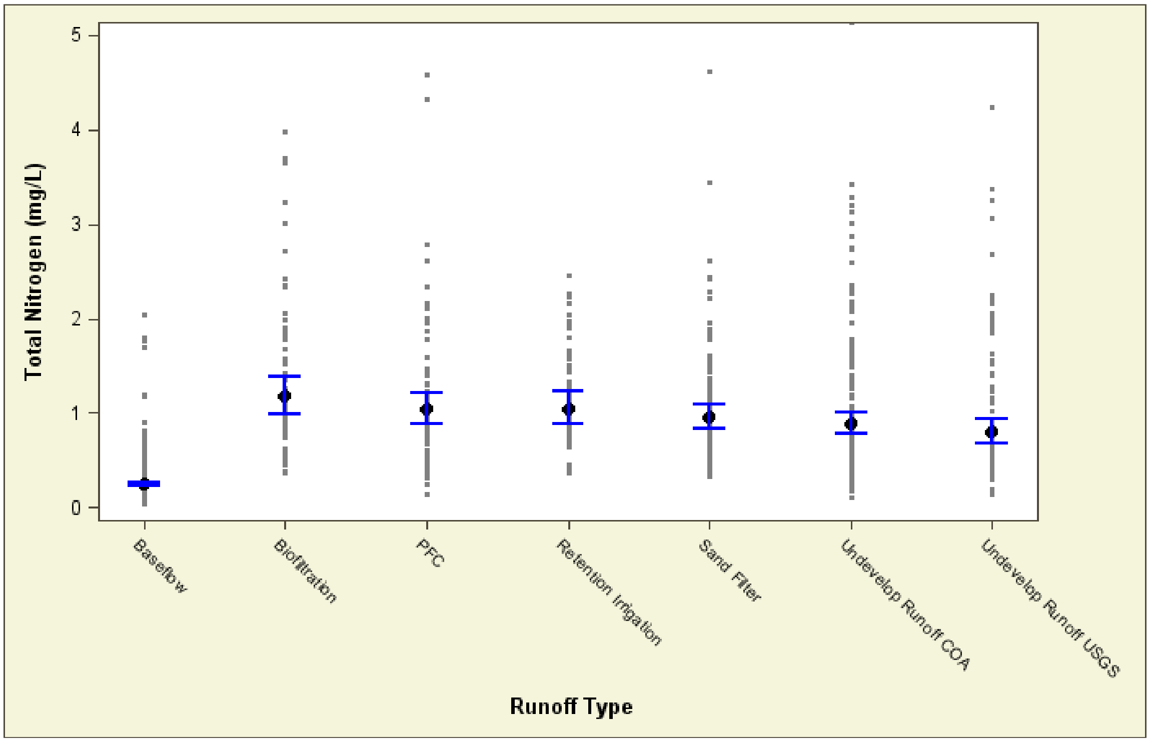


Figure 8: Total nitrogen (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Dissolved Phosphorus

The mean, standard error, and 95% confidence interval for dissolved phosphorus in baseflow, biofiltration effluent, retention-irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 9. Concentrations of dissolved phosphorus in baseflow were significantly lower than in all other runoff types. In addition to the significant difference noted with baseflow, concentrations of dissolved phosphorus in undeveloped runoff collected from the COA were significantly lower than concentrations in biofiltration, retention-irrigation, and sand filter effluent (Figure 9).

Table 9: Mean, standard error, and 95% confidence interval for dissolved phosphorus (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	0.009	0.0003	0.008	0.009	All
Biofiltration	0.105	0.0121	0.084	0.131	Baseflow, Retention Irrigation, Undeveloped Runoff COA, Undeveloped Runoff USGS
Retention Irrigation	0.180	0.0208	0.144	0.226	All
Sand Filter	0.054	0.0110	0.037	0.081	Baseflow, Retention Irrigation, Undeveloped Runoff COA, Undeveloped Runoff USGS
Undeveloped Runoff COA	0.018	0.0018	0.015	0.022	Baseflow, Biofiltration, Retention Irrigation, Sand Filter
Undeveloped Runoff USGS	0.016	0.0019	0.013	0.020	Baseflow, Biofiltration, Retention Irrigation, Sand Filter

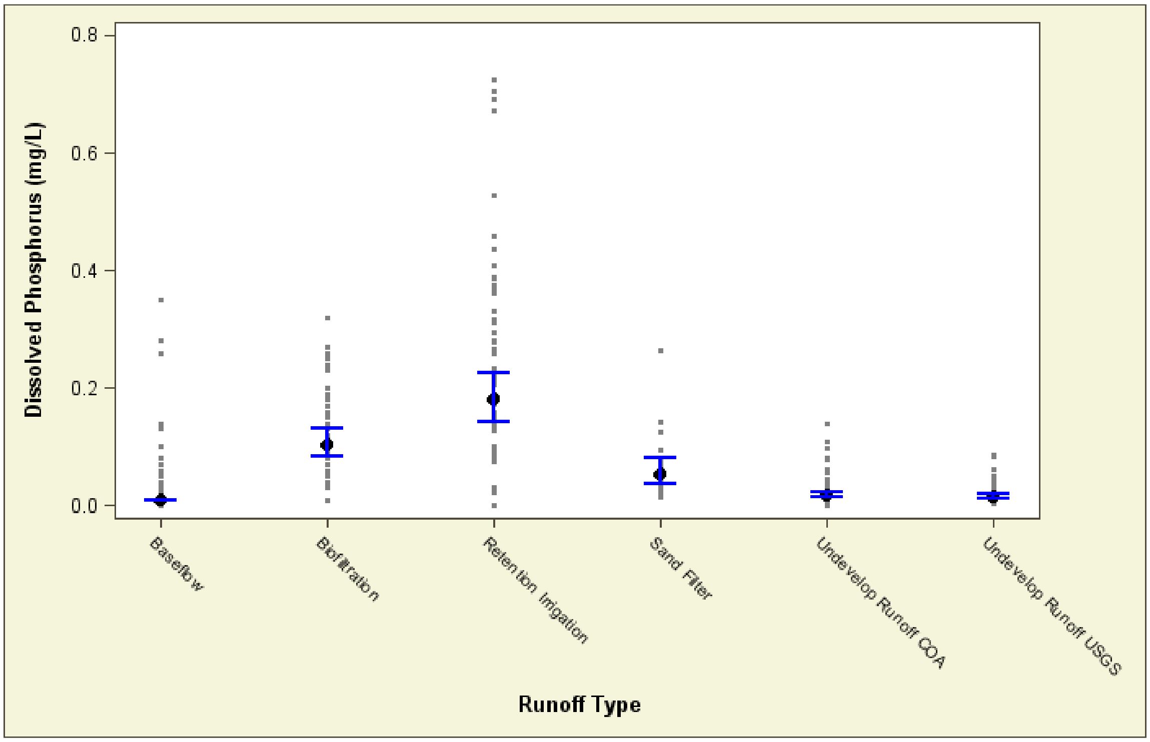


Figure 9: Dissolved phosphorus (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures.

Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Total Phosphorus

The mean, standard error, and 95% confidence interval for total phosphorus in baseflow, biofiltration effluent, PFC effluent, retention-irrigation effluent, sand filter effluent, undeveloped runoff collected by COA, and undeveloped runoff collected by the USGS can be seen in Table 10. Concentrations of total phosphorus in baseflow were significantly lower than in all other runoff types. In addition to the significant difference noted with baseflow, concentrations of total phosphorus in undeveloped runoff collected from the COA were significantly lower than concentrations in biofiltration and retention-irrigation effluent but were not significantly different from concentrations in PFC or sand filter effluent (Figure 10).

Table 10: Mean, standard error, and 95% confidence interval for total phosphorus (mg/L) from samples collected from the baseflow of Austin creeks adjacent to undeveloped land, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. The α was 0.05 to determine significant differences between runoff types.

Runoff Type	Mean	Std Error	95% CI		Sig. Diff.
Baseflow	0.014	0.001	0.013	0.015	All
Biofiltration	0.166	0.018	0.134	0.205	All
PFC	0.050	0.005	0.040	0.061	Baseflow, Biofiltration, Retention Irrigation, Sand Filter
Retention Irrigation	0.308	0.033	0.249	0.380	All
Sand Filter	0.078	0.007	0.066	0.093	Baseflow, Biofiltration, PFC, Retention Irrigation
Undeveloped Runoff COA	0.056	0.005	0.047	0.065	Baseflow, Biofiltration, Retention Irrigation
Undeveloped Runoff USGS	0.055	0.006	0.045	0.068	Baseflow, Biofiltration, Retention Irrigation

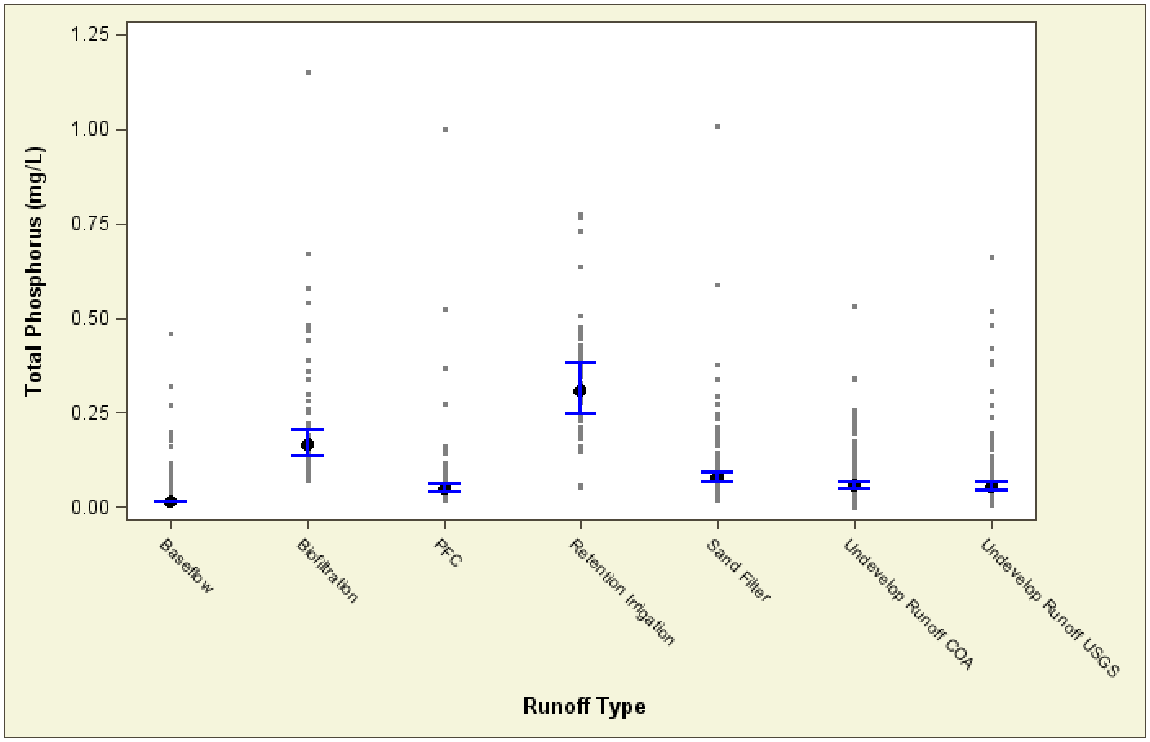


Figure 10: Total phosphorus (mg/L) from samples collected from the baseflow of undeveloped Austin creeks, stormwater runoff from undeveloped land, and effluent of various stormwater control measures. Black dots represent the mean while blue lines represent the 95% confidence interval and gray dots represent raw data.

Conclusions and Discussion

No SCM analyzed in this report meets the criterion that every parameter in the effluent has a concentration equal to or less than the concentration in undeveloped stormwater runoff collected by the COA. The following summarizes what can be discerned for testing on PFC, biofiltration, sand filters, and retention-irrigation SCMs to determine their efficacy in meeting undeveloped runoff quality (non-degradation) for parameters in the SOS ordinance.

PFC effluent contained higher concentrations than undeveloped runoff for COD and zinc. PFC effluent concentrations for *E. coli*, total organic carbon, nitrate, and dissolved phosphorus were not available and thus could not be analyzed. Another study of PFC along roadways showed that average effluent concentrations for nitrate plus nitrite were 0.40 mg/L or 0.25 mg/L depending on site location while nitrate plus nitrite concentrations in runoff from conventional asphalt were 0.43 mg/L or 0.16 mg/L, respectively (Stanard et al. 2008). In addition, the average concentration of dissolved phosphorus in PFC effluent was 0.035 mg/L or 0.028 mg/L depending on site location while the dissolved phosphorus concentrations in runoff from conventional asphalt were 0.044 mg/L or 0.033 mg/L, respectively. These means are within the ranges of the retention-irrigation and biofiltration effluent concentrations for nitrate but fall somewhere between sand filter effluent and undeveloped runoff collected by the COA for dissolved phosphorus. The means from Stanard et al. (2008) and the computed means from this report are not directly comparable. The means estimated in a lognormal model, as in this report, are smaller than arithmetic means for highly skewed data because the largest values have less impact on the computed mean. Further analysis would be necessary to determine if PFC effluent concentrations of nitrate and dissolved phosphorus were different from concentrations in undeveloped stormwater collected by the COA.

Biofiltration and sand filter effluent data contained all analyzed parameters, while and retention-irrigation effluent data contained all but *E. coli*. Concentrations of COD, TSS, zinc, *E. coli*, and total organic carbon were not significantly higher in biofiltration, retention-irrigation, or sand filter effluent when compared to concentrations in undeveloped stormwater runoff collected by the COA and thus currently are not parameters of concern regarding infiltration without a liner.

Nitrate and dissolved phosphorus concentrations were significantly higher in sand filter effluent when compared to the concentrations found in undeveloped stormwater runoff collected by the COA. In order to reduce the nitrate concentrations from the effluent it may be necessary to irrigate the effluent into a vegetated field. The upper most layer of soil, also known as 'topsoil', contains the most biological activity and is the most active layer of soil for nitrogen cycling by microbial activity and plant uptake. Denitrification, the transformation from nitrate to nitrogen gas, occurs mostly in the upper 10-15 cm of soil where organic carbon concentrations are high and becomes less significant with depth (Burt et al. 1999). Direct injection of nitrate into the subsurface may result in a higher amount of nitrate leaching when compared to surface application (Cameron et al. 1996). Phosphorus attenuation through biological uptake can also be improved by irrigating a field with effluent rather than directly infiltrating into the subsurface; however, phosphorus can also be attenuated in the subsurface through adsorption and complexation by mineral surfaces (Bohn et al. 2001). In fact, practices which promote settling, filtration, adsorption, precipitation, ion exchange, and biological activity have the highest potential to remove phosphorus from effluent (Scholes et al. 2008). For dissolved phosphorus, adsorption may be the most effective practice for removal (Schechter et al. 2013). Thus directly infiltrating effluent from a sand filter into the subsurface may still allow for attenuation of excess dissolved phosphorus but would most likely not be adequate to remove excess nitrate.

Retention-irrigation effluent collected prior to distribution over the irrigation field but after treatment in a retention basin contained concentrations of dissolved phosphorus and total phosphorus that were higher than concentrations found in the undeveloped runoff collected by the COA. A proven method of removing excess phosphorus (dissolved or total) is to spread the effluent across a vegetated field and allow for attenuation through biological uptake in addition to adsorption and ion exchange that occurs in the subsurface. However, some level of phosphorus attenuation does occur in the subsurface. Literature values for phosphorus attenuation are variable and can be impacted by the phosphorus, aluminum, iron, and calcium content of the soil/media in addition to pH (Cucarella and Renman 2009; Hunt et al. 2006). Thus directly infiltrating effluent from retention-irrigation systems into the subsurface may allow for removal of the excess phosphorus but no data has currently been analyzed to determine the answer to this question. Further investigation could include work to determine the capacity for removing phosphorus from effluent in subsurface soils in Austin, TX.

Similar to the retention-irrigation effluent, dissolved phosphorus and total phosphorus concentrations in biofiltration effluent were higher than concentrations found in the undeveloped runoff collected by the COA. Again, the proven method to remove the excess phosphorus from the effluent would be to spread the effluent across a vegetated field instead of directly allowing the effluent to infiltrate into the subsurface. Maintaining this practice in the BSRZ should protect groundwater from possible contamination of excess phosphorus until the capacity of Austin soils to remove phosphorus is known. However, the data available for biofiltration effluent was small in comparison to the other runoff types analyzed in this report and further investigation of effluent concentrations should be done to fully characterize biofiltration controls. Individual SCM data was aggregated by type (retention-irrigation, biofiltration, etc.) in this report as previous analysis has not shown a significant difference in the effluent concentrations between individual retention-irrigation systems or individual sand filter systems in Austin

(COA 2009, 2013a, 2013b). Thus all SCM of the same type was assumed to have similar effluent concentration regardless of location, land use treated, drainage area, or other factors. However, the effluent from biolfilatration controls analyzed in this report was new data obtained by COA and has not been the subject of previous COA analysis. Investigation of the nutrient concentrations in the three biofiltration controls indicated that the controls were not outputting similar effluent concentrations (Appendix B, Table B1).

Nitrate was significantly higher in effluent from the COA north rain garden when compared to both of the other biofiltration controls (Appendix B, Figure B1) while total nitrogen was only higher in effluent from the COA north rain garden when compared to the COA east rain garden (Appendix B, Figure B2). Dissolved phosphorus was significantly lower in the effluent from the COA east rain garden when compared to both of the other biofiltration controls (Appendix B, Figure B3) while total phosphorus was significantly different between all three controls (Appendix B, Figure B4). Significant difference tests were done using a linear model in the R program with an alpha level set at 0.05. It is unclear why these biofiltration controls have such different effluent concentrations especially when two of the controls are adjacent to each other (COA east rain garden, COA north rain garden). More data should be collected from COA biofiltration controls to determine which conditions, if any, will result in an effluent comparable to undeveloped runoff.

The overall conclusion from this analysis is that no SCM analyzed meets the criterion that every parameter in the effluent has a concentration equal to or less than the concentration in undeveloped stormwater runoff collected by the COA. This criterion is appropriate and sufficient to inform a decision on whether SOS standards could allow unlined basins over the BSRZ. One major assumption made in this study is that infiltrating runoff below SCMs would not increase pollutant concentrations compared to the surface discharge of effluent. To test this assumption, direct measurement of basin infiltration concentrations through lysimeters or wells is necessary. Such a study would explicitly show whether or not SOS standards could be met with unlined SCMs and would provide more confident assurance of aquifer protection.

Recommendations

Changes in liner requirements to allow unlined basins over the recharge zone are not supported by the available local data. No changes to SCM liner requirements over the recharge zone should be made at this time.

Additional monitoring data from SCMs should be obtained covering all of the parameters in the SOS ordinance in order to demonstrate non-degradation for unlined stormwater basins in the BSRZ. Additional monitoring data should be obtained for all of the types of SCMs allowed by the COA ECM before unlined basins would be supportable in the BSRZ. Since the data available for biofiltration effluent was small in comparison to the other runoff types analyzed in this report, further investigation of biofiltration effluent concentrations should be done to fully characterize biofiltration control effectiveness.

Further investigation could include work to determine the capacity of subsurface soils in Austin, TX, to remove nutrients from effluent.

Specific site locations were not used in this report because a previous analysis of similar data has shown there not to be a significant difference between site effluent concentrations from retention irrigation or sand filter controls in Austin. Therefore, all SCMs of the same type were assumed to output similar effluent concentrations. Further investigation of the nutrient concentrations in the three biofiltration controls indicated that the controls were not outputting similar effluent concentrations. Additional study is recommended to determine the cause of the variation between biofiltration sites.

A study of direct infiltration quantity and quality below unlined stormwater basins in the BSRZ should be made as pilot testing for determining if a regulatory change is warranted. This would necessarily require relaxation of the standards for construction of unlined SCMs for testing. Such a study should be geared to obtain vadose zone water and groundwater samples rather than just SCM effluent. Design of such a study should be reviewed by all regulatory entities and stakeholders concerned with protection of the aquifer. A consensus on results based action items should be obtained before sampling for the study is initiated.

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Appendix A: Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Chemical Oxygen Demand (mg/L)						
Baseflow	Biofiltration	-1.5560	0.1039	-1.8729	-1.2391	< 0.0001
Baseflow	PFC	-2.0614	0.1009	-2.3695	-1.7534	< 0.0001
Baseflow	Retention Irrigation	-1.3856	0.1039	-1.7025	-1.0686	< 0.0001
Baseflow	Sand Filter	-1.1295	0.0918	-1.4095	-0.8495	< 0.0001
Baseflow	Undevelop Runoff COA	-1.4343	0.0880	-1.7027	-1.1659	< 0.0001
Baseflow	Undevelop Runoff USGS	-1.1327	0.1073	-1.4600	-0.8054	< 0.0001
Biofiltration	PFC	-0.5054	0.1153	-0.8574	-0.1534	0.0003
Biofiltration	Retention Irrigation	0.1705	0.1179	-0.1893	0.5303	1.0000
Biofiltration	Sand Filter	0.4265	0.1074	0.0988	0.7543	0.0017
Biofiltration	Undevelop Runoff COA	0.1217	0.1042	-0.1962	0.4396	1.0000
Biofiltration	Undevelop Runoff USGS	0.4233	0.1209	0.0544	0.7923	0.0105
PFC	Retention Irrigation	0.6759	0.1153	0.3239	1.0279	< 0.0001
PFC	Sand Filter	0.9319	0.1046	0.6127	1.2511	< 0.0001
PFC	Undevelop Runoff COA	0.6271	0.1013	0.3181	0.9362	< 0.0001
PFC	Undevelop Runoff USGS	0.9288	0.1184	0.5674	1.2901	< 0.0001
Retention Irrigation	Sand Filter	0.2561	0.1074	-0.0717	0.5838	0.3664
Retention Irrigation	Undevelop Runoff COA	-0.0488	0.1042	-0.3667	0.2691	1.0000
Retention Irrigation	Undevelop Runoff USGS	0.2529	0.1209	-0.1161	0.6219	0.7755
Sand Filter	Undevelop Runoff COA	-0.3048	0.0921	-0.5860	-0.0237	0.0209
Sand Filter	Undevelop Runoff USGS	-0.0032	0.1107	-0.3410	0.3346	1.0000
Undevelop Runoff COA	Undevelop Runoff USGS	0.3016	0.1076	-0.0266	0.6299	0.1096

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Total Suspended Solids (mg/L)						
Baseflow	Biofiltration	-1.6811	0.1661	-2.1871	-1.1751	< 0.0001
Baseflow	PFC	-1.9618	0.1576	-2.4418	-1.4817	< 0.0001
Baseflow	Retention Irrigation	-2.3945	0.1650	-2.8970	-1.8920	< 0.0001
Baseflow	Sand Filter	-2.2572	0.1384	-2.6789	-1.8355	< 0.0001
Baseflow	Undevelop Runoff COA	-3.2577	0.1285	-3.6491	-2.8663	< 0.0001
Baseflow	Undevelop Runoff USGS	-4.1320	0.1586	-4.6150	-3.6490	< 0.0001
Biofiltration	PFC	-0.2806	0.2151	-0.9359	0.3746	1.0000
Biofiltration	Retention Irrigation	-0.7134	0.2206	-1.3853	-0.0415	0.0265
Biofiltration	Sand Filter	-0.5761	0.2015	-1.1899	0.0377	0.0912
Biofiltration	Undevelop Runoff COA	-1.5766	0.1948	-2.1700	-0.9832	< 0.0001
Biofiltration	Undevelop Runoff USGS	-2.4509	0.2158	-3.1083	-1.7934	< 0.0001
PFC	Retention Irrigation	-0.4328	0.2142	-1.0853	0.2198	0.9165
PFC	Sand Filter	-0.2954	0.1945	-0.8880	0.2972	1.0000
PFC	Undevelop Runoff COA	-1.2960	0.1876	-1.8674	-0.7246	< 0.0001
PFC	Undevelop Runoff USGS	-2.1702	0.2093	-2.8079	-1.5326	< 0.0001
Retention Irrigation	Sand Filter	0.1373	0.2006	-0.4736	0.7483	1.0000
Retention Irrigation	Undevelop Runoff COA	-0.8632	0.1938	-1.4536	-0.2728	0.0002
Retention Irrigation	Undevelop Runoff USGS	-1.7375	0.2149	-2.3922	-1.0827	< 0.0001
Sand Filter	Undevelop Runoff COA	-1.0005	0.1718	-1.5239	-0.4771	< 0.0001
Sand Filter	Undevelop Runoff USGS	-1.8748	0.1953	-2.4698	-1.2798	< 0.0001
Undevelop Runoff COA	Undevelop Runoff USGS	-0.8743	0.1884	-1.4482	-0.3004	< 0.0001

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Zinc (µg/L)						
Baseflow	Biofiltration	0.5483	0.1878	-0.0252	1.1218	0.0770
Baseflow	PFC	-1.3960	0.1829	-1.9544	-0.8376	< 0.0001
Baseflow	Retention Irrigation	-0.7865	0.1878	-1.3601	-0.2130	0.0007
Baseflow	Sand Filter	-1.2320	0.1713	-1.7552	-0.7088	< 0.0001
Baseflow	Undevelop Runoff COA	-0.7880	0.1645	-1.2902	-0.2858	< 0.0001
Baseflow	Undevelop Runoff USGS	-0.7275	0.2138	-1.3802	-0.0749	0.0151
Biofiltration	PFC	-1.9443	0.1878	-2.5178	-1.3708	< 0.0001
Biofiltration	Retention Irrigation	-1.3348	0.1926	-1.9230	-0.7466	< 0.0001
Biofiltration	Sand Filter	-1.7803	0.1766	-2.3195	-1.2411	< 0.0001
Biofiltration	Undevelop Runoff COA	-1.3363	0.1699	-1.8552	-0.8174	< 0.0001
Biofiltration	Undevelop Runoff USGS	-1.2758	0.2180	-1.9414	-0.6102	< 0.0001
PFC	Retention Irrigation	0.6095	0.1878	0.0360	1.1830	0.0263
PFC	Sand Filter	0.1640	0.1713	-0.3592	0.6872	1.0000
PFC	Undevelop Runoff COA	0.6080	0.1645	0.1058	1.1102	0.0051
PFC	Undevelop Runoff USGS	0.6685	0.2138	0.0158	1.3211	0.0391
Retention Irrigation	Sand Filter	-0.4454	0.1766	-0.9847	0.0938	0.2512
Retention Irrigation	Undevelop Runoff COA	-0.0015	0.1699	-0.5204	0.5174	1.0000
Retention Irrigation	Undevelop Runoff USGS	0.0590	0.2180	-0.6066	0.7246	1.0000
Sand Filter	Undevelop Runoff COA	0.4440	0.1515	-0.0187	0.9066	0.0743
Sand Filter	Undevelop Runoff USGS	0.5045	0.2040	-0.1183	1.1272	0.2878
Undevelop Runoff COA	Undevelop Runoff USGS	0.0605	0.1982	-0.5447	0.6657	1.0000

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
E. coli (MPN/100mL)						
Baseflow	Biofiltration	-2.6961	0.5120	-4.1401	-1.2522	< 0.0001
Baseflow	Sand Filter	-4.2671	0.1442	-4.6737	-3.8606	< 0.0001
Baseflow	Undevelop Runoff COA	-4.5275	0.1634	-4.9882	-4.0668	< 0.0001
Baseflow	Undevelop Runoff USGS	-4.3330	0.1785	-4.8365	-3.8294	< 0.0001
Biofiltration	Sand Filter	-1.5710	0.5234	-3.0471	-0.0949	0.0283
Biofiltration	Undevelop Runoff COA	-1.8314	0.5290	-3.3233	-0.3394	0.0059
Biofiltration	Undevelop Runoff USGS	-1.6368	0.5339	-3.1426	-0.1311	0.0229
Sand Filter	Undevelop Runoff COA	-0.2604	0.1962	-0.8137	0.2930	1.0000
Sand Filter	Undevelop Runoff USGS	-0.0659	0.2090	-0.6554	0.5237	1.0000
Undevelop Runoff COA	Undevelop Runoff USGS	0.1945	0.2227	-0.4335	0.8226	1.0000
Total Organic Carbon (mg/L)						
Biofiltration	Retention Irrigation	-0.0890	0.1148	-0.4130	0.2350	1.0000
Biofiltration	Sand Filter	0.3017	0.1064	0.0013	0.6021	0.0482
Biofiltration	Undevelop Runoff COA	-0.0500	0.1016	-0.3368	0.2368	1.0000
Biofiltration	Undevelop Runoff USGS	-0.1302	0.1127	-0.4483	0.1880	1.0000
Retention Irrigation	Sand Filter	0.3907	0.1064	0.0903	0.6911	0.0027
Retention Irrigation	Undevelop Runoff COA	0.0390	0.1016	-0.2478	0.3258	1.0000
Retention Irrigation	Undevelop Runoff USGS	-0.0412	0.1127	-0.3593	0.2769	1.0000
Sand Filter	Undevelop Runoff COA	-0.3517	0.0920	-0.6115	-0.0919	0.0015
Sand Filter	Undevelop Runoff USGS	-0.4319	0.1042	-0.7259	-0.1379	0.0004
Undevelop Runoff COA	Undevelop Runoff USGS	-0.0802	0.0992	-0.3602	0.1999	1.0000

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Nitrate (mg/L)						
Baseflow	Biofiltration	-1.7403	0.1530	-2.1906	-1.2901	< 0.0001
Baseflow	Retention Irrigation	-0.9793	0.1530	-1.4295	-0.5290	< 0.0001
Baseflow	Sand Filter	-2.0850	0.1293	-2.4655	-1.7046	< 0.0001
Baseflow	Undevelop Runoff COA	-1.3290	0.1188	-1.6785	-0.9795	< 0.0001
Baseflow	Undevelop Runoff USGS	-0.7573	0.1480	-1.1927	-0.3219	< 0.0001
Biofiltration	Retention Irrigation	0.7611	0.2048	0.1583	1.3638	0.0032
Biofiltration	Sand Filter	-0.3447	0.1878	-0.8972	0.2079	1.0000
Biofiltration	Undevelop Runoff COA	0.4113	0.1807	-0.1204	0.9430	0.3459
Biofiltration	Undevelop Runoff USGS	0.9830	0.2011	0.3913	1.5748	< 0.0001
Retention Irrigation	Sand Filter	-1.1057	0.1878	-1.6583	-0.5532	< 0.0001
Retention Irrigation	Undevelop Runoff COA	-0.3498	0.1807	-0.8815	0.1820	0.7981
Retention Irrigation	Undevelop Runoff USGS	0.2220	0.2011	-0.3698	0.8137	1.0000
Sand Filter	Undevelop Runoff COA	0.7560	0.1611	0.2819	1.2301	< 0.0001
Sand Filter	Undevelop Runoff USGS	1.3277	0.1837	0.7872	1.8682	< 0.0001
Undevelop Runoff COA	Undevelop Runoff USGS	0.5717	0.1764	0.0525	1.0909	0.0185

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Total Nitrogen (mg/L)						
Baseflow	Biofiltration	-1.5543	0.0918	-1.8342	-1.2744	< 0.0001
Baseflow	PFC	-1.4330	0.0890	-1.7043	-1.1617	< 0.0001
Baseflow	Retention Irrigation	-1.4439	0.0918	-1.7238	-1.1639	< 0.0001
Baseflow	Sand Filter	-1.3534	0.0789	-1.5940	-1.1129	< 0.0001
Baseflow	Undevelop Runoff COA	-1.2846	0.0735	-1.5086	-1.0605	< 0.0001
Baseflow	Undevelop Runoff USGS	-1.1653	0.0895	-1.4382	-0.8924	< 0.0001
Biofiltration	PFC	0.1213	0.1167	-0.2345	0.4771	1.0000
Biofiltration	Retention Irrigation	0.1104	0.1189	-0.2521	0.4729	1.0000
Biofiltration	Sand Filter	0.2008	0.1093	-0.1322	0.5338	1.0000
Biofiltration	Undevelop Runoff COA	0.2697	0.1054	-0.0516	0.5910	0.2246
Biofiltration	Undevelop Runoff USGS	0.3890	0.1172	0.0319	0.7461	0.0198
PFC	Retention Irrigation	-0.0109	0.1167	-0.3667	0.3449	1.0000
PFC	Sand Filter	0.0795	0.1069	-0.2463	0.4053	1.0000
PFC	Undevelop Runoff COA	0.1484	0.1030	-0.1654	0.4622	1.0000
PFC	Undevelop Runoff USGS	0.2677	0.1150	-0.0827	0.6181	0.4227
Retention Irrigation	Sand Filter	0.0904	0.1093	-0.2426	0.4234	1.0000
Retention Irrigation	Undevelop Runoff COA	0.1593	0.1054	-0.1620	0.4806	1.0000
Retention Irrigation	Undevelop Runoff USGS	0.2786	0.1172	-0.0785	0.6357	0.3708
Sand Filter	Undevelop Runoff COA	0.0689	0.0944	-0.2188	0.3565	1.0000
Sand Filter	Undevelop Runoff USGS	0.1882	0.1073	-0.1390	0.5153	1.0000
Undevelop Runoff COA	Undevelop Runoff USGS	0.1193	0.1034	-0.1960	0.4345	1.0000

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Dissolved Phosphorus (mg/L)						
Baseflow	Biofiltration	-2.4941	0.1202	-2.8477	-2.1405	< 0.0001
Baseflow	Retention Irrigation	-3.0354	0.1202	-3.3890	-2.6818	< 0.0001
Baseflow	Sand Filter	-1.8249	0.2038	-2.4246	-1.2251	< 0.0001
Baseflow	Undevelop Runoff COA	-0.7501	0.1051	-1.0594	-0.4407	< 0.0001
Baseflow	Undevelop Runoff USGS	-0.6005	0.1219	-0.9593	-0.2417	< 0.0001
Biofiltration	Retention Irrigation	-0.5414	0.1627	-1.0201	-0.0626	0.0136
Biofiltration	Sand Filter	0.6692	0.2315	-0.0118	1.3502	0.0588
Biofiltration	Undevelop Runoff COA	1.7440	0.1519	1.2970	2.1910	< 0.0001
Biofiltration	Undevelop Runoff USGS	1.8936	0.1640	1.4110	2.3761	< 0.0001
Retention Irrigation	Sand Filter	1.2106	0.2315	0.5295	1.8916	< 0.0001
Retention Irrigation	Undevelop Runoff COA	2.2854	0.1519	1.8383	2.7324	< 0.0001
Retention Irrigation	Undevelop Runoff USGS	2.4349	0.1640	1.9524	2.9175	< 0.0001
Sand Filter	Undevelop Runoff COA	1.0748	0.2240	0.4157	1.7339	< 0.0001
Sand Filter	Undevelop Runoff USGS	1.2243	0.2324	0.5406	1.9081	< 0.0001
Undevelop Runoff COA	Undevelop Runoff USGS	0.1496	0.1533	-0.3016	0.6007	1.0000

Appendix A (cont.): Model output for the multiple comparisons test between SCM effluent, baseflow, and undeveloped runoff pollutant concentrations. The α was 0.05, thus comparisons with p-values less than 0.05 were considered to be significantly different.

Runoff1	Runoff2	Difference	Std Err	95% Confidence Interval		p-value
Total Phosphorus (mg/L)						
Baseflow	Biofiltration	-2.4765	0.1150	-2.8268	-2.1262	< 0.0001
Baseflow	PFC	-1.2690	0.1113	-1.6081	-0.9300	< 0.0001
Baseflow	Retention Irrigation	-3.0944	0.1150	-3.4447	-2.7441	< 0.0001
Baseflow	Sand Filter	-1.7273	0.0964	-2.0212	-1.4335	< 0.0001
Baseflow	Undevelop Runoff COA	-1.3872	0.0907	-1.6635	-1.1109	< 0.0001
Baseflow	Undevelop Runoff USGS	-1.3780	0.1120	-1.7192	-1.0368	< 0.0001
Biofiltration	PFC	1.2075	0.1490	0.7535	1.6614	< 0.0001
Biofiltration	Retention Irrigation	-0.6179	0.1518	-1.0803	-0.1555	0.0011
Biofiltration	Sand Filter	0.7491	0.1383	0.3279	1.1704	< 0.0001
Biofiltration	Undevelop Runoff COA	1.0893	0.1343	0.6801	1.4985	< 0.0001
Biofiltration	Undevelop Runoff USGS	1.0985	0.1495	0.6429	1.5540	< 0.0001
PFC	Retention Irrigation	-1.8254	0.1490	-2.2793	-1.3714	< 0.0001
PFC	Sand Filter	-0.4583	0.1352	-0.8702	-0.0464	0.0153
PFC	Undevelop Runoff COA	-0.1182	0.1312	-0.5178	0.2815	1.0000
PFC	Undevelop Runoff USGS	-0.1090	0.1467	-0.5559	0.3380	1.0000
Retention Irrigation	Sand Filter	1.3670	0.1383	0.9458	1.7883	< 0.0001
Retention Irrigation	Undevelop Runoff COA	1.7072	0.1343	1.2980	2.1164	< 0.0001
Retention Irrigation	Undevelop Runoff USGS	1.7164	0.1495	1.2608	2.1719	< 0.0001
Sand Filter	Undevelop Runoff COA	0.3401	0.1188	-0.0219	0.7022	0.0903
Sand Filter	Undevelop Runoff USGS	0.3493	0.1358	-0.0644	0.7630	0.2152
Undevelop Runoff COA	Undevelop Runoff USGS	0.0092	0.1318	-0.3923	0.4106	1.0000

Appendix B: Supplemental information regarding additional analysis of the difference between pollutant concentrations in individual biofiltration effluent.

Table B1: Mean and stand error for nutrient data collected from individual biofiltration control effluents.

	COA East Rain Garden		COA North Rain Garden		Gillis Park Biofiltration	
Parameter	Mean	Std Error	Mean	Std Error	Mean	Std Error
Nitrate (mg/L)	0.37	0.07	0.79	0.08	0.36	0.14
Total Nitrogen (mg/L)	0.97	0.22	1.75	0.41	2.05	0.25
Dissolved Phosphorus (mg/L)	0.069	0.023	0.192	0.026	0.204	0.043
Total Phosphorus (mg/L)	0.112	0.025	0.243	0.029	0.454	0.048

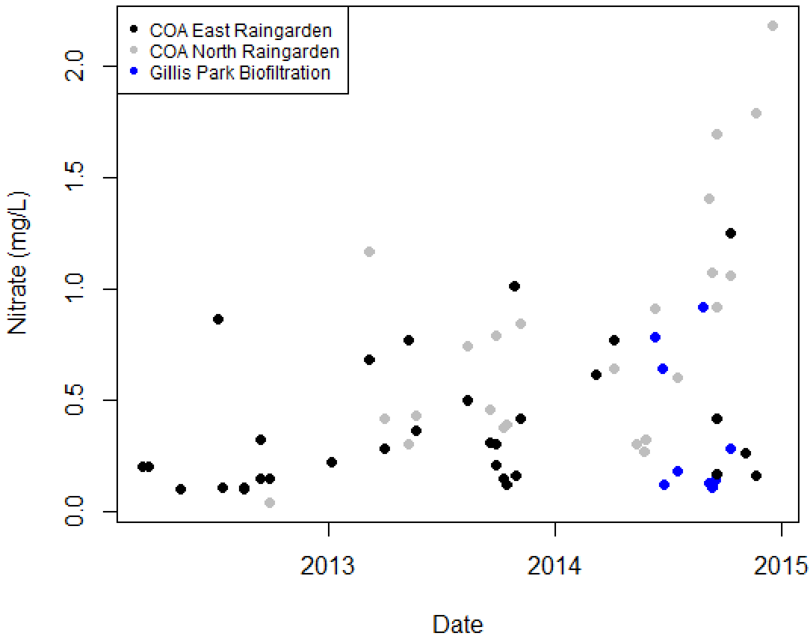

Figure B1: Nitrate (mg/L) concentrations collected at individual biofiltration controls in Austin, TX.

Appendix B (cont.): Supplemental information regarding additional analysis of the difference between pollutant concentrations in individual biofiltration effluent.

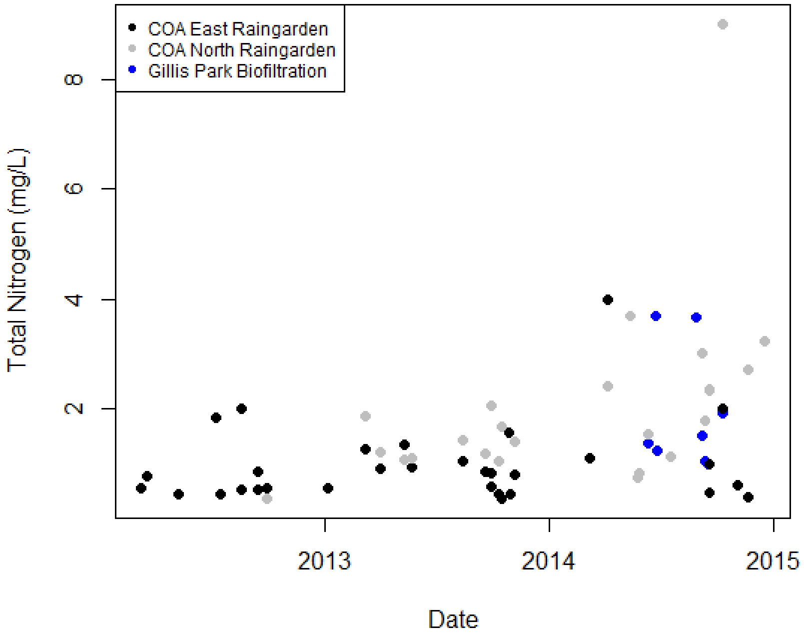

Figure B2: Total nitrogen (mg/L) concentrations collected at three biofiltration controls in Austin, TX.

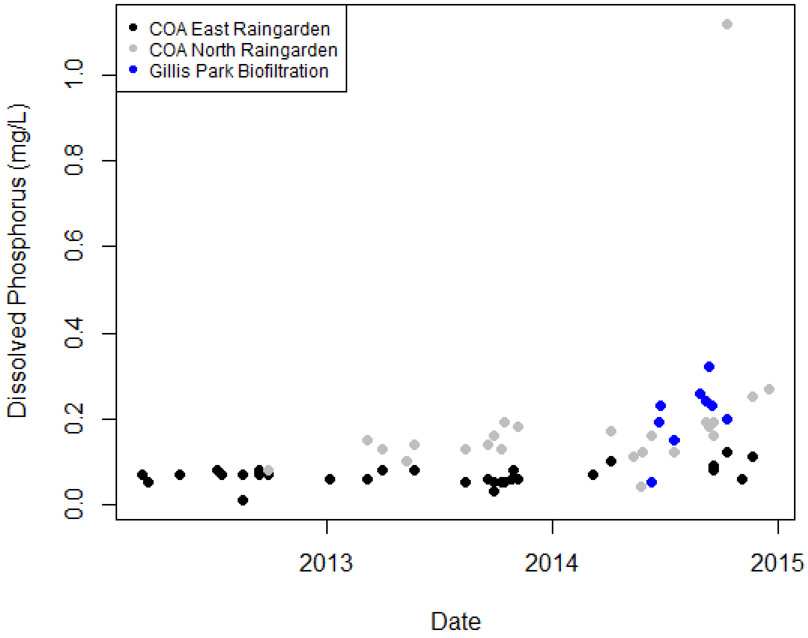

Figure B3: Dissolved phosphorus (mg/L) concentrations collected at three biofiltration controls in Austin, TX.

Appendix B (cont.): Supplemental information regarding additional analysis of the difference between pollutant concentrations in individual biofiltration effluent.

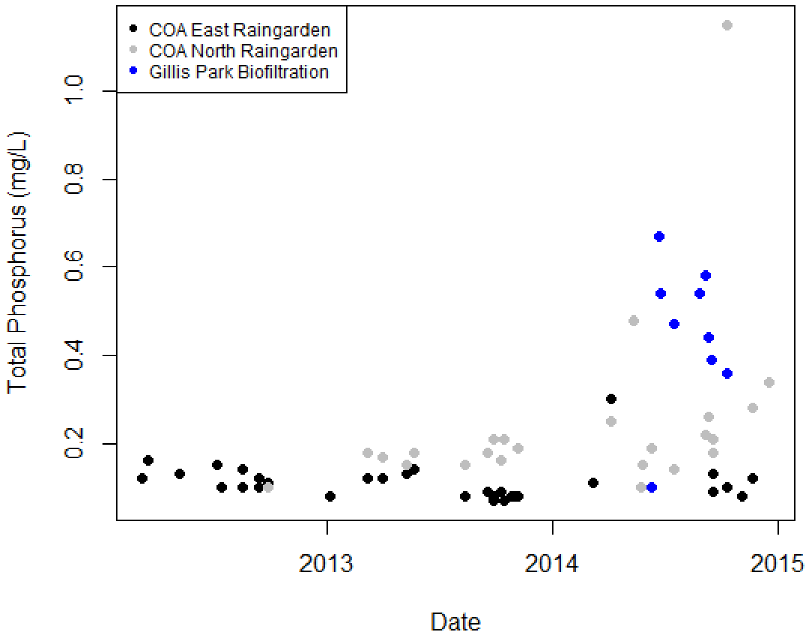

Figure B4: Total phosphorus (mg/L) concentrations collected at three biofiltration controls in Austin, TX.