

Comparison of water quality at locations currently receiving wastewater effluent irrigation to locations planned for future wastewater effluent irrigation

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Abstract

The dominant form of wastewater disposal in the environmentally sensitive Barton Springs Zone of the Edwards Aquifer is to apply treated wastewater effluent over an irrigation field rather than to allow the effluent to be directly discharged to a stream. A Texas Land Application Permit (TLAP) is required from the Texas Commission on Environmental Quality (TCEQ) in order to dispose of 5,000 gallons per day or more of treated wastewater over an irrigation field. However, the current permitting criteria may not be enough to keep the wastewater from negatively impacting adjacent streams. The City of Austin Watershed Protection Department conducted monitoring to determine how irrigation practices from TLAP facilities may influence water quality in downgradient water resources. Samples were collected during non-storm influenced conditions at springs or downgradient stream sites adjacent to two existing TLAP facilities and two proposed facilities that have not yet begun effluent irrigation in Travis County, Texas. Results indicated that chloride, nitrate/nitrite, sodium, and strontium isotopes were elevated at both sites impacted by existing TLAP facilities. Water quality downgradient of one of the TLAP facilities also contained elevated concentrations of calcium, potassium, alkalinity, and conductivity. The drainage network to the second TLAP facility is large and complex. Non-effluent waters may be diluting some water quality parameters and it is unlikely that WPD staff can make useful inferences about the protective nature of this TLAP. Thus, the site will be dropped from the second phase of this monitoring effort.

INTRODUCTION

The Texas Commission on Environmental Quality (TCEQ) issues permits for treated wastewater effluent disposal of 5,000 gallons per day or more via no discharge irrigation through the Texas Land Application Permit (TLAP) program under Title 30 of the Texas Administrative Code chapters 222 and 309. TLAP facilities are the dominant method of centralized wastewater disposal in the Barton Springs Zone (Herrington et al. 2011). Permit requirements for storage, treatment limits, and irrigation areas in the contributing zone of the Edwards Aquifer are highly variable (Ross 2011). TLAP facilities may have unintended negative impacts on the nutrient concentrations of adjacent streams and springs (Mahler et al. 2011; Turner 2010). Effluent irrigation via similar methods under a TCEQ Beneficial Reuse Authorization (Title 30 Texas Administrative Code Chapter 210) has been documented to impact adjacent water quality (Porrás et al. 2016). Data highlighting the impacts of TLAP facilities on the high quality surface and groundwater resources of the Barton Springs Zone are extremely limited (Ross 2011). Revisions to the Texas Administrative Code may be necessary to achieve TLAP requirements with consistent limitations that are protective of water quality. This report will quantify potential impact of TLAP facilities on adjacent water resources through the characterization of resources adjacent to separate currently operating TLAP facilities and two resources adjacent to facilities that are not yet operating.

METHODS

Site Description

Springs or downgradient stream sites adjacent to permitted TLAP facilities which have not yet begun effluent irrigation include Rimrock Spring, North Sycamore Creek at Foster Ranch Road, and Little Barton upstream of Hamilton Pool Road. Rimrock Spring and North Sycamore Creek at Foster Ranch Road are adjacent to Travis County Municipal Utility District (MUD) No. 4 (WQ0014430001) (Figure 1). The proposed facility consists of an activated sludge process plant, includes one storage pond with a total capacity of 140 acre-feet of storage, and is authorized to dispose of treated domestic wastewater effluent at a daily average flow not to exceed 600,000 gallons per day through surface irrigation over 220 acres in the final phase of the permit (application rate of 3.0 acre-feet per year per acre). The permit requires an ultraviolet (UV) light system for the disinfection process and contains effluent limitations for 5-day carbonaceous biochemical oxygen demand (CBOD5), total suspended solids, and ammonia.

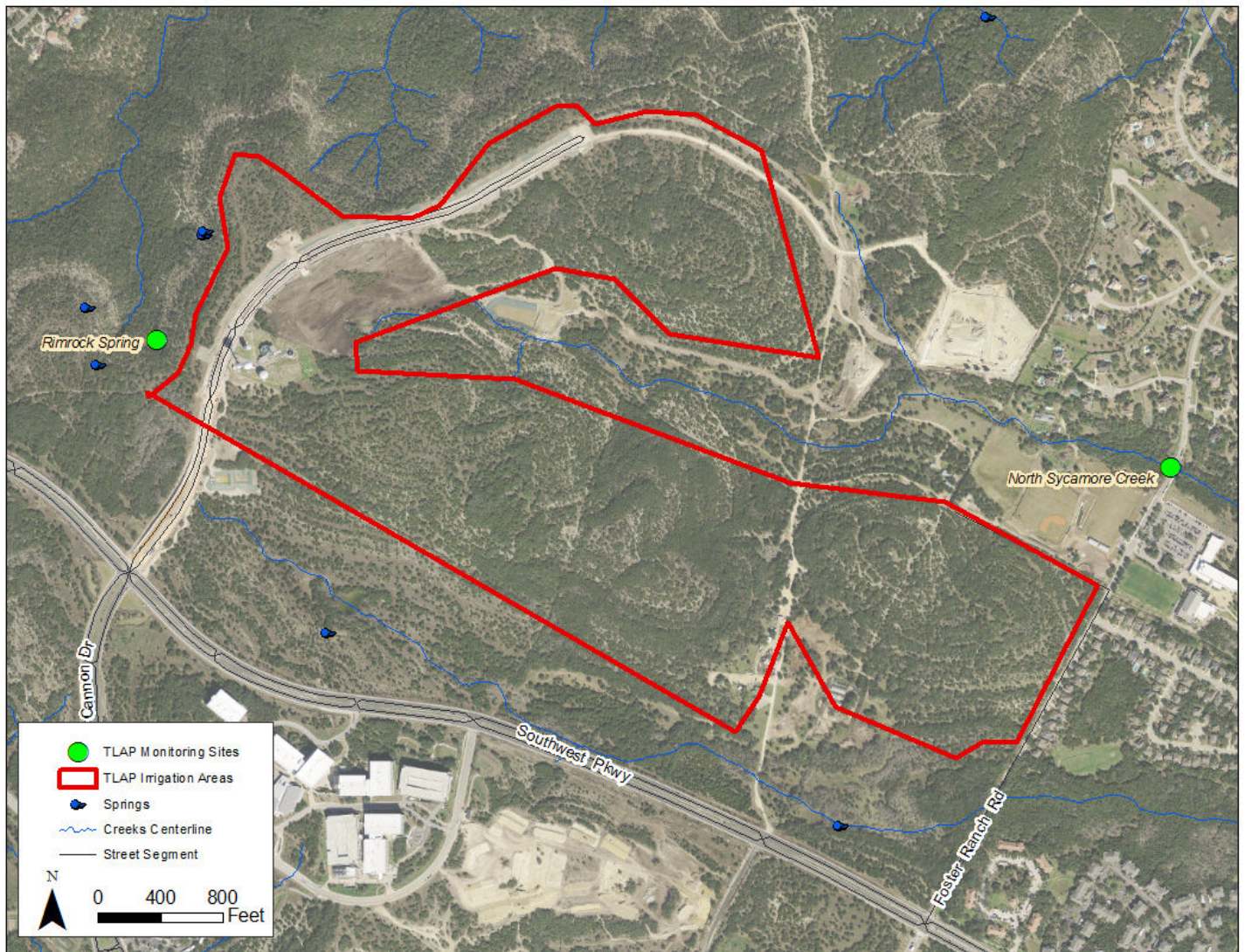


Figure 1. Rimrock Spring and North Sycamore at Foster Ranch sample sites at the future TLAP field Travis County Municipal Utility District (MUD) No. 4.

The sample site Little Barton Creek Upstream of Hamilton Pool (Figure 2) is adjacent to Lazy Nine MUD 1A and Sweetwater Austin Properties LLC (hereafter referred to as Lazy Nine) (WQ0014629001) in the Little Barton Creek Watershed. The proposed facility consists of an activated sludge process plant, includes two storage ponds with a total capacity of 90.3 acre-feet of storage in the final phase, and is authorized to dispose of treated domestic wastewater effluent at a daily average flow not to exceed 490,000 gallons per day through surface irrigation over 199.5 acres in the

final phase of the permit (application rate of 2.75 acre-feet per year per acre). The permit allows for the use of a chlorine contact chamber for the disinfection process and contains effluent limitations for CBOD5 and total suspended solids.

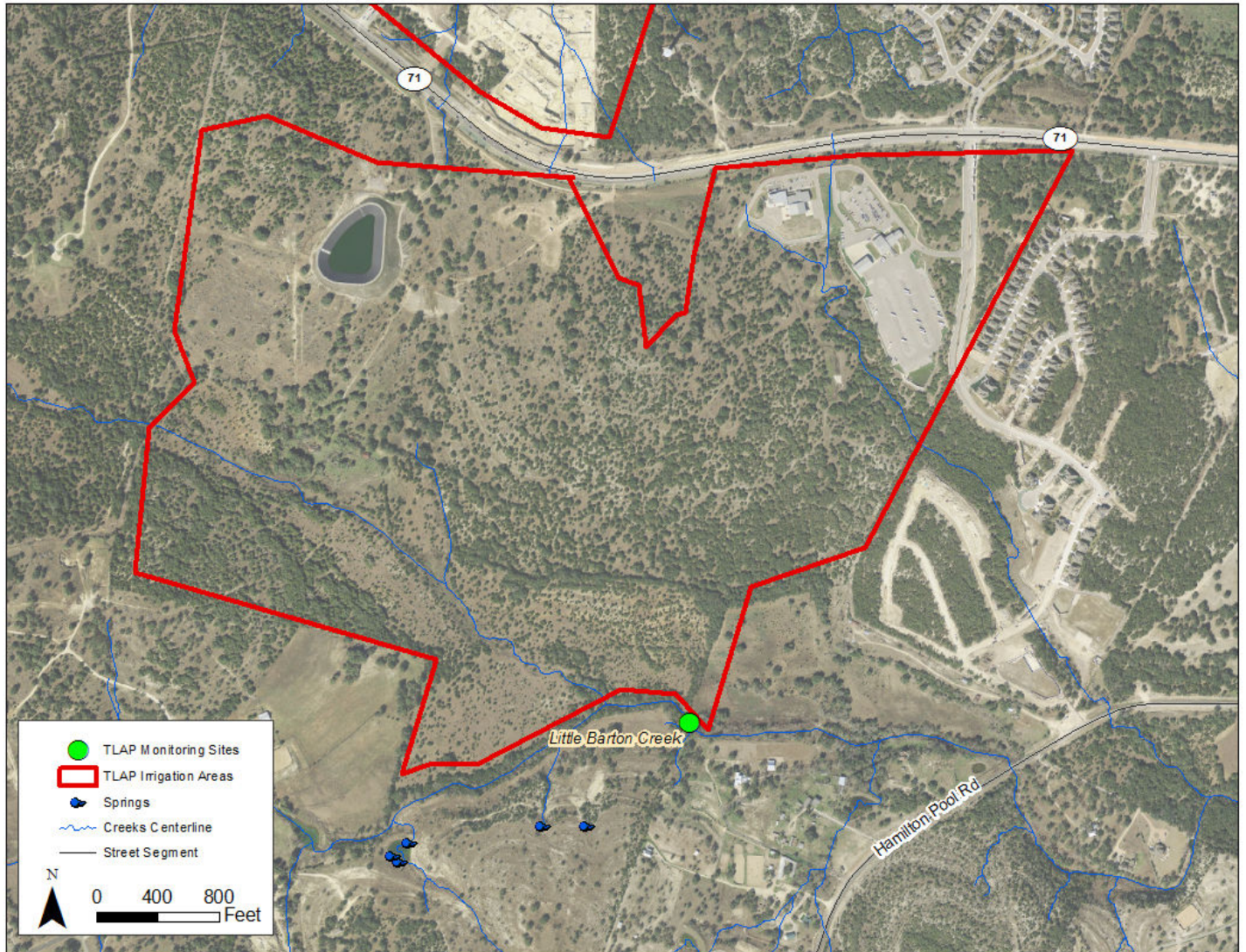


Figure 2. Little Barton Creek Upstream of Hamilton Pool sample site at Lazy Nine MUD 1A and Sweetwater Austin Properties LLC.

Springs or downgradient stream sites adjacent to permitted TLAP facilities which are currently irrigating with wastewater effluent include Short Spring Branch at Barton Creek and Barton Scenic Bluff Spring. The sample site Short Spring Branch at Barton Creek is adjacent to the Lost Creek Wastewater Treatment Facility (Figure 3) and is located on Short Spring Branch, a tributary to Barton Creek. The permit (WQ0011319001) was first issued to the Lost Creek MUD but was transferred to the City of Austin in 2009. The facility consists of one contact stabilization activated sludge plant and one complete mix activated sludge plant which are operated in parallel, includes three storage ponds with a total capacity of 69.2 acre-feet of storage in the final phase, and is authorized to dispose of treated domestic wastewater effluent at a daily average flow not to exceed 520,000 gallons per day through surface irrigation over 308.42 acres (102 acres of the Lost Creek Golf Course, 20 acres of the adjacent 38 acre tract of land, and 186.42 acres of the Coore-Crenshaw Golf Course) in the final phase of the permit. The facility is also authorized to transfer 220,000 gallons per day to Travis County MUD No. 4 (WQ0013206001). The application rate of the irrigated land is not to exceed 2.75 acre-feet per year per acre, but if the full 308.42 acres is used for irrigation of the 520,000 gallons per day of effluent, the application rate would be closer to 1.89 acre-feet per year per acre. The permit requires a chlorine contact chamber for the disinfection process and contains effluent limitations for CBOD5 and total suspended solids.

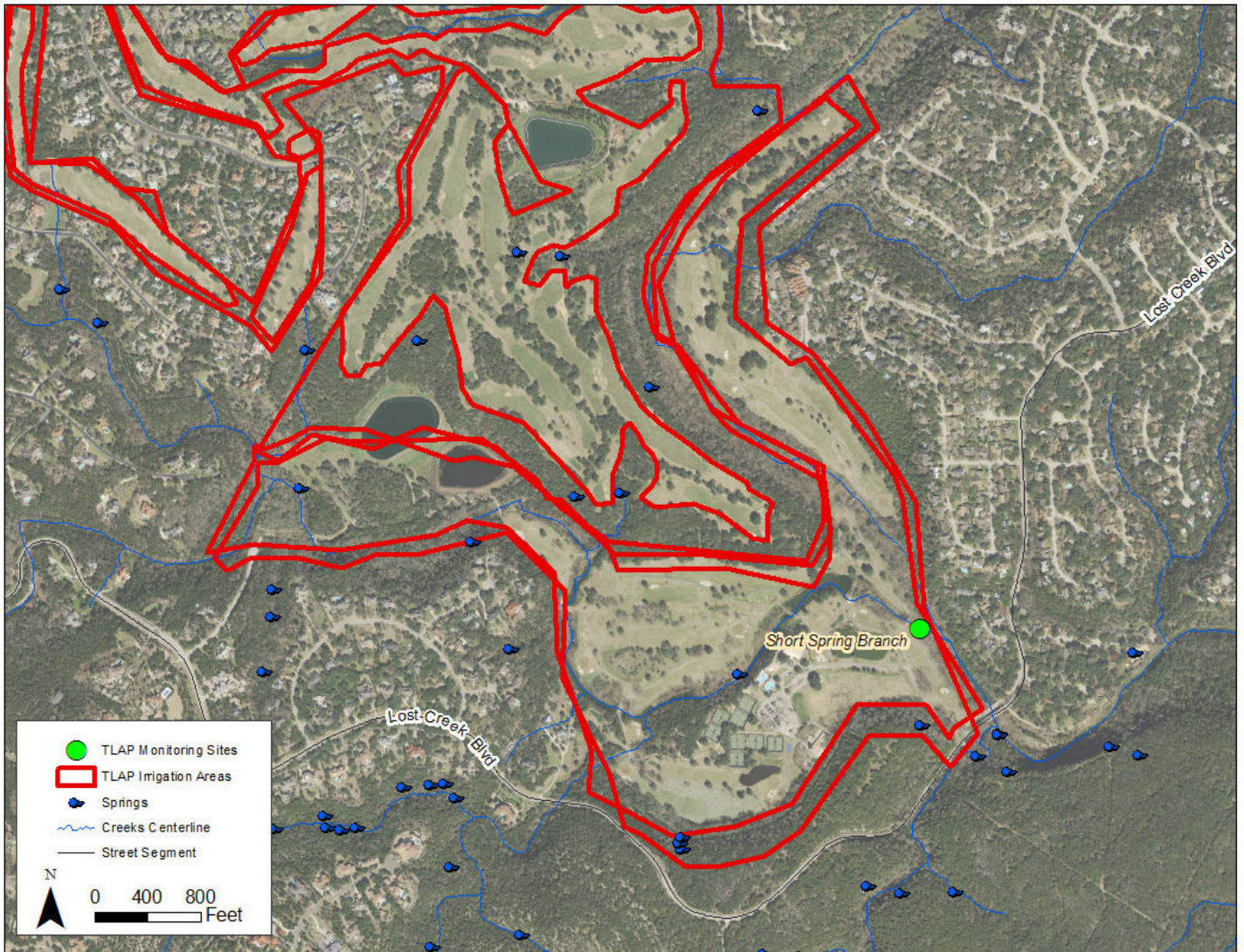


Figure 3. Short Spring Branch sample site at Lost Creek Wastewater Treatment Facility.

The sample site Barton Scenic Bluff Spring is adjacent to Barton Creek West (WQ0012786001) (Figure 4) in the Barton Creek watershed. The facility consists of a contact stabilization activated sludge process plant, includes one storage pond with a total capacity of 62.7 acre-feet of storage, and is authorized to dispose of treated domestic wastewater effluent at a daily average flow not to exceed 126,000 gallons per day through surface irrigation over 53.3 acres (application rate of 2.65 acre-feet per year per acre). The permit requires a chlorine contact chamber for the disinfection process and contains effluent limitations for CBOD5 and total suspended solids.

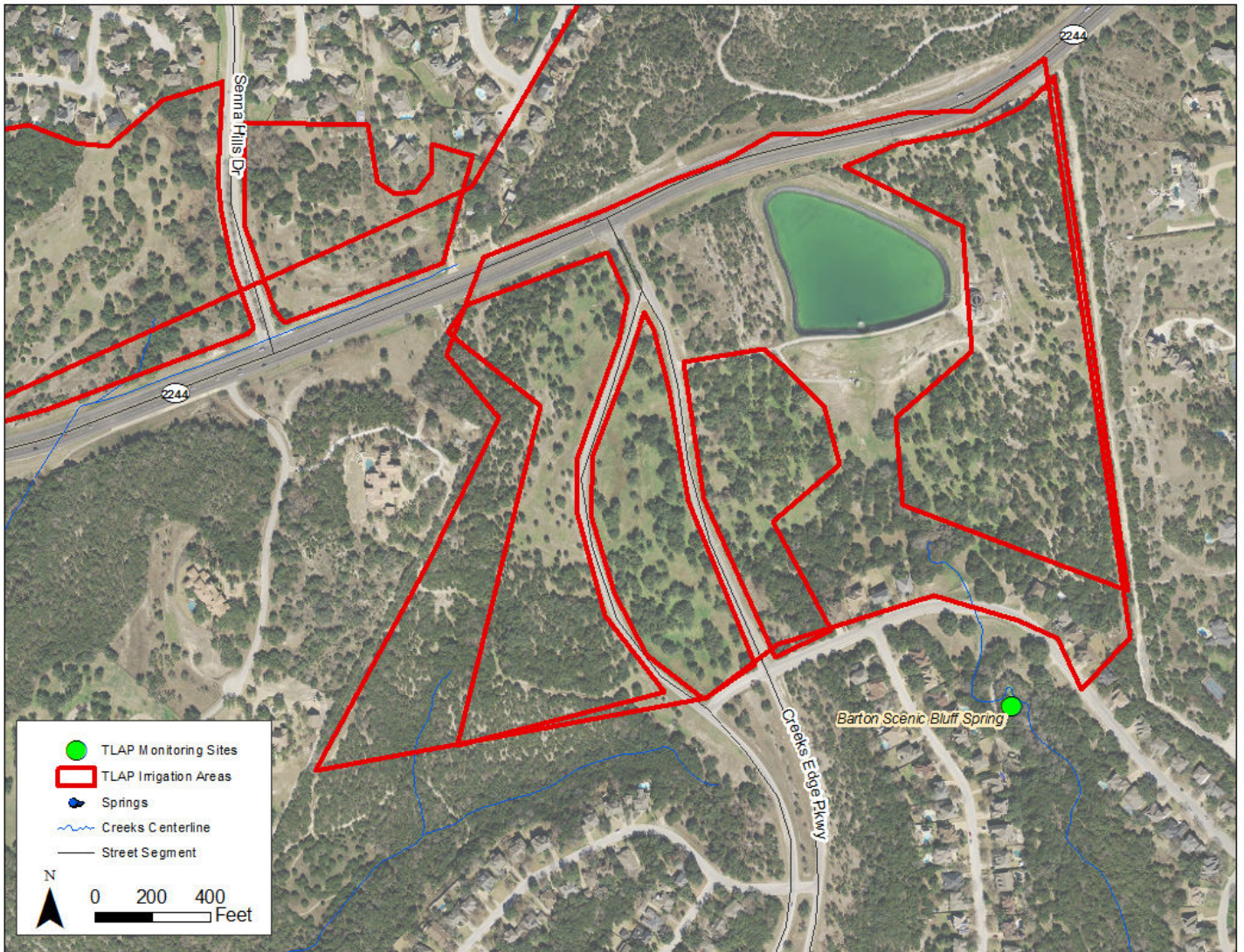


Figure 4. Barton Scenic Bluff Spring sample site at Barton Creek West.

Data Collection

Data collection was originally scheduled to begin in July 2012, and continue once per month for two years or until the Lazy Nine and Travis County MUD No. 4 began actively using their irrigation fields. Adherence to this schedule led to a large number of sampling events in which flow was not present. In response, a more flexible schedule was adopted so that sample events could be scheduled when sites were flowing (Table 1). Sample events occurred under baseflow conditions pursuant to the Watershed Protection Department Standard Operating Procedures which limited the influence of antecedent rainfall.

Table 1: Schedule of water quality sample collection at each site.

DATE	Existing operating TLAP		Future proposed TLAP		
	Barton Scenic Bluff Spring	Short Spring Branch	Little Barton Creek	Rimrock Spring	North Sycamore Creek
28-AUG-2012	X	X	X		
09-APR-2013	X	X	X	X	
24-OCT-2013	X	X	X	X	X
20-NOV-2013				X	X
22-JUL-2014	X			X	X
20-OCT-2014					X
21-OCT-2014	X	X	X		
04-DEC-2014	X	X	X		X
21-JAN-2015	X	X	X	X	X
17-FEB-2015					X
18-FEB-2015	X	X	X	X	
30-MAR-2015					X
31-MAR-2015	X	X	X	X	
29-APR-2015	X	X	X	X	X
28-JUL-2015	X	X	X	X	X
20-AUG-2015	X	X	X	X	X
02-DEC-2015	X	X	X	X	X
06-JAN-2016	X	X	X	X	X
03-FEB-2016	X	X	X	X	X
17-FEB-2016	X	X	X	X	X
25-APR-2016				X	X
09-JUN-2016				X	X
12-DEC-2016	X	X	X	X	X

Water samples were sent to Lower Colorado River Authority (LCRA) Environmental Lab Services for analysis of a suite of source water characterization parameters (Table 2). Strontium isotope analysis was sub-contracted to the Massachusetts Institute of Technology (MIT) Isotope Lab in the Department of Earth, Atmospheric and Planetary Sciences, while the nitrogen and oxygen isotope analysis was sub-contracted to Isotech Laboratories. Water samples were collected following the procedures outlined in the Water Resource Evaluation Standard Operating Procedures Manual (WRE SOP 2016). Samples used for analysis of dissolved metals were filtered in the field using a 0.45 µm filter.

Table 2: Suite of parameters collected every sampling event.

Dissolved Metals	Total Metals	Ions	Nutrients	Isotopes	Field	Other
Aluminum	Arsenic	Chloride	Ammonia as N	Strontium 86/87 Ratio	Conductivity	Alkalinity
Barium	Boron	Bromide	Nitrate/Nitrite as N	Nitrogen-15	Dissolved Oxygen	<i>Escherichia coli (E. coli)</i>
Calcium	Magnesium	Fluoride	Kjeldahl Nitrogen as N	Oxygen-18	pH	Organic Carbon
Copper	Potassium	Sulfate	Orthophosphorus as P		Water Temperature	Total Suspended Solids
Iron	Sodium		Phosphorus as P			Volatile Suspended Solids
Lead	Strontium					
Zinc						

Analytical Methods

Nitrogen-15 and Oxygen-18 isotopes were collected at all sites; however, samples containing less than 1 mg/L of nitrate/nitrite contain insufficient concentrations to carry out isotope analysis. Thus, samples collected at Barton Scenic Bluff Spring, which contained nitrate/nitrite concentration greater than 1 mg/L, were analyzed for N-15 and O-18 isotopes. Accordingly, due to the low number of results, these two isotopes will not be explored in this analysis.

Parameters were split into three categories *post hoc* based on the percentage of values below the detection limit at each site. The first category consisted of parameters which had a high percentage of values below the detection limit, the second contained parameters with an intermediate percentage of values below the detection limit, and the third contained parameters where no values were below the detection limit. Parameters were considered to have a high percentage of values below the detection limit if over 50% of the samples were below the detection limit at the majority of sites or if the percentage of values below the detection limit was greater than 70% at one site. When greater than 50% of the values are below the detection limit and the data set contains a small number of observations, such as this data set, calculating the mean can become difficult leading to biased estimates. In fact, this parameter set contained sites with over 70% of values below the detection limit and no method is recommended for computing a mean under such conditions. Parameters were considered to contain an intermediate percentage of values below the detection limit if they contained one value below the detection limit to approximately 50% of values below the detection limit at each site. Nitrate/nitrite as N was the only parameter in this category to have more than 50% of values below the detection limit at Rimrock Spring and North Sycamore Creek with 54% and 57% respectively.

A test of equal proportions was performed on parameters with a higher percentage of values below the detection limit (Hollander and Wolfe 1999). This was done using the CHISQ option in the TABLES statement using PROC FREQ in SAS version 9.4. This procedure computes a chi-square statistic based on the frequency of values below the detection limit at each site compared to the expected frequency if each site were assumed to have an equal proportion of values below the detection limit. If the chi-square statistic is large enough than the proportion of values below the detection limit is different between sites.

Estimates of the mean along with the 95% confidence intervals of the mean were computed for a parameter at a site if less than 50% of the values for that parameter were below the detection limit. Estimates were computed for nitrate/nitrite as N for all sites even though the percentage of points below the detection limit were above 50% at Rimrock Spring and North Sycamore Creek, thus the nitrate/nitrite as N estimates may be high at these sites. Several recommendations exist for computing means with values below the detection limit including maximum likelihood estimation (MLE), the Kaplan-Meier method, and robust Regression on Order Statistics (ROS). MLE computes a mean and a standard deviation based on a likelihood equation for values above the detection limit and below the detection limit but requires a data set with greater than 50 detected values (Helsel and Cohn 1988, Singh and Nocerino 2002, Shumway et al. 2002). The Kaplan-Meier method is a nonparametric method initially used for survival analysis where unknown values were greater than a threshold but has been adopted to work with data where the unknown value is less than a threshold. The Kaplan-Meier method estimates the cumulative distribution function associated with the data where the mean equals the area underneath this curve (Klein and Moeschberger 2003). The downside of the Kaplan-Meier method is that when only one detection limit is present in the data then the method is equivalent to simple substitution of the detection threshold. For the robust ROS method, detected values are put into a probability plot and a linear regression line is calculated from those points. The linear equation is used to impute the values below detection. These imputed values are combined with the real data values above the detection limit to calculate summary statistics (Helsel 2012). The mean and 95% confidence intervals were computed using the simple substitution method and the robust ROS method; however, values imputed through the robust ROS method were continuously above the detection limit for every parameter except *E. coli*. This lead to slightly higher estimates of the mean when compared to using the simple substitution method. Thus the mean and 95% confidence intervals reported in this document are based off of the simple substitution method using the threshold of detection as the filled in value for all parameters except *E. coli* where the robust ROS method was used to find the estimates.

The experimental design fits a hierarchical model system because the samples are clustered within sites which are then clustered into whether or not the site is downgradient of a currently operating TLAP irrigation field. The intraclass correlation coefficient is a statistic that is used to quantify the degree to which observations within a cluster resemble each other (Koch 1982). If used in a linear mixed model the intraclass correlation can give you the proportion of the total

variance in the response variable which is accounted for by the clustering. Given the following equation for a mixed model:

$$Y_{ij} = \mu + u_i + \varepsilon_{ij}$$

where Y_{ij} is the j observation of the response variable in i^{th} cluster, μ is an overall mean, u_i is a random effect shared by all values in the i^{th} cluster, and ε_{ij} is unaccounted for error. Then the intraclass correlation can be computed as

$$\frac{\sigma_u^2}{\sigma_u^2 + \sigma_\varepsilon^2}$$

where σ_u^2 is the variance of u and σ_ε^2 is the variance of ε . The intraclass correlation coefficient was computed when only the clustering effect of being downgradient of an operating TLAP irrigation field was considered as a random effect and again when the clustering effect of site location was introduced into the model.

Concentrations were compared between sites for group of parameters with an intermediate percentage of values below the detection limit and the group of parameters where none of the values were below the detection limit. For the former, concentrations were compared using the Kruskal Wallis test and the Dwass, Steel, Critchlow-Fligner multiple comparison method (Hollander and Wolfe 1999). This was done using the WILCOXON and DSCF options in the NPAR1WAY procedure in SAS version 9.4. For the latter, concentrations were compared using an Analysis of Variance (ANOVA) test and the Tukey-Kramer multiple comparison method (Kutner et al. 2005).

RESULTS

Parameters in Table 3 had a high percentage of samples below the detection limit at each site. It is difficult to develop descriptive statistics about parameters when over 50% of the data is below the detection limit. Means were computed only at appropriate sites for copper, boron, and total suspended solids (Table 4) but no comparison of the mean was done for these parameters. Instead, the proportion of samples below the detection limit was compared between sites. Copper had a significantly lower proportion of samples below the detection limit at Barton Scenic Bluff Spring. Boron had a significantly higher proportion of samples below the detection limit at Rimrock Spring and North Sycamore Creek, and the proportion of samples collected at Barton Scenic Bluff Spring was significantly lower than at Little Barton Creek. Total phosphorus had a significantly lower proportion of samples below the detection limit at Short Spring Branch when compared to Barton Scenic Bluff Spring and North Sycamore Creek. Total Suspended Solids had a significantly higher proportion of sample below the detection limit when compared to Short Spring Branch and North Sycamore Creek. Volatile Suspended Solids had a significantly lower proportion of samples below the detection limit in North Sycamore Creek when compared to Barton Scenic Bluff Spring, Short Spring Branch, and Little Barton Creek (Table 3).

Parameters in Table 5 had an intermediate proportion of samples under the detection limit. Site means were computed and site comparisons were done using nonparametric methods. While the percentage of samples below detection limit for nitrate/nitrite was slightly higher than 50% at Rimrock Spring and North Sycamore Creek, the mean was still computed at these sites to compare against the other sites which had very few samples below the detection limit for nitrate/nitrite (Table 5).

Concentrations of bromide were significantly higher at Barton Scenic Bluff Spring when compared to Little Barton Creek and Rimrock Spring, which contained concentrations of bromide that were significantly lower than at any other site (Table 7). These results complement the intraclass correlation analysis because there are significant bromide concentration differences from site to site but the two sites impacted by active TLAPs are different from the three sites not impacted by active TLAPs. Chloride concentrations were significantly highest at Barton Scenic Bluff Spring but concentrations at Short Spring Branch were significantly higher than the other three sites and concentrations at Little Barton Creek were significantly higher than at Rimrock Spring or North Sycamore Creek. Sites impacted by active TLAPs had the highest concentrations of chloride which is why the intraclass correlation for chloride was substantial even when the site location was included. Fluoride was significantly highest at Rimrock Spring followed by Little Barton Creek. Nitrate/nitrite was significantly highest at Barton Scenic Bluff Spring but was not significantly different at other sites. Concentrations at Short Spring Branch were elevated but not significantly different from the non-TLAP impacted sites. This corresponds to the intraclass correlation suggesting that the nitrate/nitrite concentrations may be impacted

more by the presence of a TLAP and less on the site location. Total Kjeldal Nitrogen at Little Barton Creek was significantly lower than at all other sites. Organic carbon concentrations were highest at Short Spring Branch and North Sycamore Creek but lowest at Little Barton Creek. *E. coli* counts were highest at Little Barton Creek and North Sycamore Creek but were low at Rimrock Spring.

The intraclass correlation for the intermediately censored parameters when only the TLAP function was included in the model showed that 0 to 48% of the variance could be explained by whether or not an active TLAP drained to the site location (Table 6). However, when site location was included in the model, all of the TLAP function intraclass correlations except for nitrate/nitrite and chloride dropped to 0% and the site location explained 16 to 53% of the variance. Nitrate/nitrite and chloride showed the highest indication that an active TLAP was impacting the concentrations found in the samples since the variance explained by TLAP function ranged from 35 to 38% after site location was included (Table 6).

Parameters in Table 8 contained only those parameters that were always above the detection limit. No special analyses were needed to compute means or compare site mean concentrations. The intraclass correlation for the uncensored parameters when only the TLAP function was included in the model showed that 0 to 68% of the variance could be explained by whether or not an active TLAP drained to the site location (Table 9). However, when site location was included in the model, all of the TLAP function intraclass correlations except for calcium, potassium, sodium, conductivity, water temperature, and strontium 86/87 ratio dropped to 0% and the site location explained 0 to 77% of the variance.

Table 3: Number of total samples, samples under the detection limit, and percentage of samples under the detection limit for each of the 5 sites receiving drainage from the 4 TLAP irrigation areas. Barton Creek West and Lost Creek TLAPs were functioning during the sampling period while the Lazy Nine and Travis County MUD No. 4 were yet to be irrigated. Parameters were highly censored (50-90% below detection). Site percentages marked with a different letter (A, B, C) were significantly different for that parameter.

Parameter	Detection Limit	Barton Creek West			Lost Creek			Lazy Nine			Travis County MUD No.4					
		Barton Scenic Bluff Spring			Short Spring Branch			Little Barton Creek			Rimrock Spring			North Sycamore Creek		
		Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent
Aluminum	1.5 µg/L	15	11	73	16	12	75	15	11	73	13	10	77	7	4	57
Copper	0.4 µg/L	15	6	40 ^A	16	14	88 ^B	15	14	93 ^B	13	12	92 ^B	7	7	100 ^B
Iron	0.02 mg/L	15	15	100	16	16	100	15	15	100	13	13	100	7	7	100
Lead	0.4 µg/L	15	15	100	16	16	100	15	15	100	13	13	100	7	7	100
Zinc	1.5 µg/L	15	13	87	16	14	88	15	15	100	13	11	85	7	7	100
Arsenic	0.7 µg/L	15	15	100	16	14	88	15	15	100	13	13	100	7	7	100
Boron	0.02 mg/L	15	0	0 ^A	16	1	6 ^{AB}	15	4	27 ^B	13	11	85 ^C	7	5	71 ^C
Ammonia as N	0.008 mg/L	15	14	93	16	12	75	15	14	93	13	9	69	7	6	86
Orthophosphorus	0.004 mg/L	14	14	100	16	15	94	15	15	100	13	13	100	7	7	100
Total Phosphorus	0.008 mg/L	15	15	100 ^B	16	11	69 ^A	15	13	87 ^{AB}	13	12	92 ^{AB}	7	7	100 ^B
Total Suspended Solids	1 or 2 mg/L	15	11	73 ^B	16	5	31 ^A	15	6	40 ^{AB}	12	6	50 ^{AB}	7	1	14 ^A
Volatile Suspended Solids	1 or 2 mg/L	15	15	100 ^B	16	15	94 ^B	15	15	100 ^B	12	10	83 ^{AB}	7	4	57 ^A

Table 4: Means and 95% confidence interval for highly censored parameters where the site percentage of data below detection limit was 50% or less.

Parameter	Barton Creek West			Lost Creek			Lazy Nine			Travis County MUD No.4						
	Barton Scenic Bluff Spring			Short Spring Branch			Little Barton Creek			Rimrock Spring			North Sycamore Creek			
	Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		
Copper (µg/L)	1.08	0.89	1.32													
Boron (mg/L)	0.247	0.197	0.309	0.099	0.080	0.123	0.060	0.048	0.075							
Total Suspended Solids (mg/L)				1.36	1.06	1.76	1.87	1.44	2.43	2.34	1.74	3.13	4.31	2.94	6.33	

Table 5: Number of total samples, samples under the detection limit, and percentage of samples under the detection limit for each of the 5 sites receiving drainage from the 4 TLAP irrigation areas. Barton Creek West and Lost Creek TLAPs were functioning during the sampling period while the Lazy Nine and Travis County MUD No. 4 were yet to be irrigated. Parameters were intermediately censored (1-50% below detection limit).

Parameter	Detection Limit	Barton Creek West			Lost Creek			Lazy Nine			Travis County MUD No.4					
		Barton Scenic Bluff Spring			Short Spring Branch			Little Barton Creek			Rimrock Spring			North Sycamore Creek		
		Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent
Bromide	0.008 mg/L	14	1	7	16	1	6	15	1	7	13	2	15	7	0	0
Chloride	0.4 mg/L	14	0	0	16	0	0	15	1	7	13	0	0	7	0	0
Fluoride	0.02 mg/L	13	1	8	15	0	0	14	0	0	12	0	0	7	0	0
Nitrate/Nitrite as N	0.008 mg/L	15	0	0	16	0	0	15	3	20	13	7	54	7	4	57
Total Kjeldahl Nitrogen	0.080 mg/L	15	3	20	16	0	0	15	5	33	13	4	31	7	0	0
Organic Carbon	0.2 mg/L	15	0	0	16	0	0	15	0	0	13	1	8	7	0	0
<i>E. coli</i>	1 MPN/100 mL	15	5	33	16	0	0	15	1	7	12	3	25	7	1	14

Table 6: Intraclass correlation for intermediately censored parameters (1-50% below detection limit) for a model that includes only a TLAP function cluster and a model which contains cluster effects of TLAP function and site location.

Parameter	ICC TLAP Function only	ICC TLAP function and Site Location	
		TLAP Function	Site Location
Bromide	0.25	0	0.52
Chloride	0.48	0.35	0.47
Fluoride	0.26	0	0.53
Nitrate/Nitrite as N	0.42	0.38	0.16
Total Kjeldahl Nitrogen	0.07	0	0.23
Organic Carbon	0	0	0.34
<i>E. coli</i>	0.05	0	0.40

Table 7: Means and 95% confidence interval for intermediately censored parameters. Site means marked with a different letter (A, B, C, D) were significantly different for that parameter.

Parameter	Barton Creek West			Lost Creek			Lazy Nine			Travis County MUD No.4					
	Barton Scenic Bluff Spring			Short Spring Branch			Little Barton Creek			Rimrock Spring			North Sycamore Creek		
	Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval	
Bromide (mg/L)	0.204 ^C	0.177	0.230	0.158 ^{BC}	0.133	0.183	0.131 ^B	0.106	0.157	0.038 ^A	0.010	0.065	0.168 ^{BC}	0.131	0.205
Chloride (mg/L)	112.2 ^D	103.6	120.9	46.3 ^C	38.2	54.4	29.5 ^B	21.1	37.9	14.9 ^A	5.9	23.9	12.9 ^A	0.7	25.2
Fluoride (mg/L)	0.114 ^A	0.096	0.135	0.143 ^A	0.122	0.168	0.211 ^B	0.179	0.249	0.403 ^C	0.337	0.482	0.139 ^A	0.110	0.176
Nitrate/Nitrite as N (mg/L)	1.762 ^B	1.014	3.061	0.365 ^A	0.214	0.624	0.143 ^A	0.082	0.249	0.152 ^A	0.084	0.275	0.106 ^A	0.047	0.239
Total Kjeldahl Nitrogen (mg/L)	0.253 ^B	0.186	0.344	0.319 ^B	0.237	0.429	0.107 ^A	0.079	0.145	0.265 ^B	0.191	0.369	0.318 ^B	0.203	0.498
Organic Carbon (mg/L)	1.97 ^B	1.64	2.37	3.00 ^C	2.51	3.59	1.36 ^A	1.13	1.64	2.91 ^{BC}	2.40	3.55	3.86 ^C	2.95	5.05
E. coli (MPN/100mL)	47 ^{AB}	43	50	34 ^A	31	37	190 ^B	183	197	18 ^A	16	21	269 ^B	257	282

Table 8: Number of total samples, samples under the detection limit, and percentage of samples under the detection limit for each of the 5 sites receiving drainage from the 4 TLAP irrigation areas. Barton Creek West and Lost Creek TLAPs were functioning during the sampling period while the Lazy Nine and Travis County MUD No. 4 were yet to be irrigated. Parameters were uncensored (0% below detection limit).

Parameter	Detection Limit	Barton Creek West			Lost Creek			Lazy Nine			Travis County MUD No.4					
		Barton Scenic Bluff Spring			Short Spring Branch			Little Barton Creek			Rimrock Spring			North Sycamore Creek		
		Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent	Total	Under Limit	Percent
Barium	0.4 µg/L	15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Calcium	0.07 mg/L	15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Magnesium	0.07 mg/L	15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Potassium	0.07 mg/L	15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Sodium	0.07 mg/L	15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Strontium	0.4 µg/L	15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Sulfate	0.4 mg/L	14	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Alkalinity	20 mg/L	14	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Conductivity		15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Dissolved Oxygen		14	0	0	15	0	0	14	0	0	12	0	0	7	0	0
pH		15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Water Temperature		15	0	0	16	0	0	15	0	0	13	0	0	7	0	0
Strontium 86/87		13	0	0	14	0	0	13	0	0	11	0	0	6	0	0

Table 9: Intraclass correlation for uncensored parameters for a model that includes only a TLAP function cluster and a model which contains cluster effects of TLAP function and site location.

Parameter	ICC TLAP Function only	ICC TLAP function and Site Location	
		TLAP Function	Site Location
Barium	0	0	0.67
Calcium	0.34	0.1	0.72
Magnesium	0.08	0	0.65
Potassium	0.41	0.26	0.43
Sodium	0.56	0.41	0.5
Strontium	0.4	0	0.77
Sulfate	0.05	0	0.55
Alkalinity	0.01	0	0.57
Conductivity	0.27	0.08	0.61
Dissolved Oxygen	0	0	0.51
pH	0.25	0	0.81
Water Temperature	0.09	0.08	0
Strontium 86/87	0.68	0.47	0.48

Concentrations of barium at Little Barton Creek and Barton Scenic Bluff Spring were significantly higher than at other locations with no difference between the other three locations (Table 10). Calcium concentrations were different between site locations with Barton Scenic Bluff Spring samples containing the highest concentrations followed by Short Spring Branch and Little Barton Creek, then North Sycamore Creek, and finally Rimrock Spring. This corresponds well to the intraclass correlation which showed site location to explain a large amount of variation in calcium data. While both sites impacted by active TLAPs have higher concentrations of calcium, Little Barton Creek also contains calcium concentrations close to Short Spring Branch concentrations so the variance explained by the presence of TLAP impacts is relatively low. Magnesium was also site dependent with Rimrock Spring containing the highest concentrations and Short Spring Branch the lowest concentrations. Potassium concentrations were highest at Barton Scenic Bluff Spring and lowest at Little Barton Creek and North Sycamore Creek. The trend in potassium concentrations is similar to the trend for calcium except that Rimrock Spring contains higher concentrations of potassium instead of Little Barton Creek which contains higher concentrations of calcium. Sodium concentrations at Barton Scenic Bluff Spring were significantly higher than at other sites followed by Short Spring Branch. The intraclass correlation for sodium was high for both the presence of an active TLAP and the site location because the active TLAP locations contained high concentrations but were not similar to each other. Strontium concentrations at Rimrock Spring were significantly higher than at other sites followed by Little Barton Creek. Sulfate concentrations were significantly lowest at Sycamore Creek. Alkalinity at Barton Scenic Bluff Spring was significantly higher than at other sites. Conductivity at Barton Scenic Bluff Spring was significantly higher than at other sites while conductivity at North Sycamore Creek was significantly lower than at other sites. Dissolved Oxygen was significantly lower at Barton Scenic Bluff Spring and Rimrock Spring. The pH at Barton Scenic Bluff Spring was almost neutral and significantly lower than at the other sites while the pH at North Sycamore Creek was more basic and significantly higher than at other sites. Water temperature was significantly higher at Barton Scenic Bluff Spring when compared to Rimrock Spring which is why the intraclass correlation showed some variance explained by the presence of an active TLAP for water temperature. The strontium 86/87 ratio was significantly highest at Barton Scenic Bluff Spring followed by Short Spring Branch, the two Travis County MUD sites, and was lowest at Little Barton Creek. The intraclass correlation was high for the presence of an active TLAP in both models for strontium 86/87 because the values at both sites downgradient of active TLAPs were significantly higher than at the three sites not yet impacted by TLAP irrigation.

Table 10: Means and 95% confidence interval for uncensored parameters. Site means marked with a different letter (A, B, C, D) were significantly different for that parameter.

Parameter	Barton Creek West			Lost Creek			Lazy Nine			Travis County MUD No.4					
	Barton Scenic Bluff Spring			Short Spring Branch			Little Barton Creek			Rimrock Spring			North Sycamore Creek		
	Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval		Mean	95% Confidence Interval	
Barium (µg/L)	47.8 ^B	44.2	51.7	33.3 ^A	30.9	35.9	54.3 ^B	50.2	58.7	33.4 ^A	30.7	36.3	30.2 ^A	26.9	33.8
Calcium (mg/L)	127.9 ^D	123.7	132.0	91.8 ^{BC}	87.8	95.8	94.4 ^C	90.3	98.6	74.6 ^A	70.1	79.1	83.8 ^{AB}	77.8	89.9
Magnesium (mg/L)	30.5 ^C	28.2	33.1	20.8 ^A	19.2	22.5	26.8 ^{BC}	24.7	29.1	41.4 ^D	38.0	45.2	23.5 ^{AB}	20.9	26.4
Potassium (mg/L)	5.58 ^C	4.65	6.69	2.44 ^B	2.05	2.91	1.45 ^A	1.21	1.74	2.64 ^B	2.17	3.21	1.53 ^A	1.17	1.99
Sodium (mg/L)	67.6 ^D	64.3	70.9	29.1 ^C	25.9	32.2	18.5 ^B	15.2	21.8	9.1 ^A	5.6	12.6	7.5 ^A	2.7	12.3
Strontium (µg/L)	218 ^A	153	312	318 ^A	225	449	2462 ^B	1724	3516	12325 ^C	8404	18074	380 ^A	225	640
Sulfate (mg/L)	74.7 ^B	65.6	85.1	64.9 ^B	57.5	73.3	69.4 ^B	61.2	78.7	67.8 ^B	59.2	77.6	33.9 ^A	28.2	40.7
Alkalinity	343 ^C	327	361	249 ^A	237	260	264 ^{AB}	252	277	287 ^B	273	302	259 ^{AB}	242	278
Conductivity (µS/cm)	1097.4 ^C	1037.2	1157.6	699.4 ^B	641.1	757.7	693.4 ^{AB}	633.2	753.6	662.7 ^{AB}	598.1	727.4	549.8 ^A	461.6	637.9
Dissolved Oxygen (mg/L)	5.89 ^A	5.27	6.60	9.15 ^B	8.21	10.2	9.75 ^B	8.71	10.91	6.20 ^A	5.49	7.00	9.96 ^B	8.50	11.67
pH	6.99 ^A	6.90	7.08	7.85 ^{BC}	7.76	7.94	7.93 ^{CD}	7.83	8.02	7.69 ^B	7.59	7.78	8.14 ^D	8.01	8.28
Water Temp. (°C)	20.6 ^B	18.2	22.9	18.3 ^{AB}	16.0	20.6	17.0 ^{AB}	14.6	19.4	15.0 ^A	12.4	17.5	15.6 ^{AB}	12.1	19.1
Strontium 86/87	0.7083 ^D	0.7082	0.7083	0.7080 ^C	0.7080	0.7081	0.7076 ^A	0.7076	0.7077	0.7079 ^B	0.7078	0.7079	0.7079 ^B	0.7079	0.7079

DISCUSSION

With additional wastewater irrigation, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of receiving waters will most likely increase over time to level equal to or greater than 0.7083 with the application of wastewater irrigation. Strontium is a fairly common alkali earth element, similar to calcium and barium. In natural water, strontium is a divalent cation with a (+2) oxidation state. The size of the Sr^{2+} ion is between Ca^{2+} and K^{+} ions and can replace calcium or potassium in a variety of rock-forming minerals including K-feldspar, gypsum, plagioclase, calcium carbonate, and dolomite. Because strontium has an electron configuration similar to that of calcium, it readily substitutes for Ca in minerals. Of the only two dominant minerals containing strontium; celestite (SrSO_4) and strontianite (SrCO_3), celestite is frequently found in sedimentary rocks. These minerals and weathering of rocks is the source of strontium in groundwater and surface water. In the sedimentary rocks, the distribution of strontium is affected by strong adsorption on clay minerals, substitution of Sr^{2+} for Ca^{2+} in carbonate minerals such as in aragonite and calcite, which are the major rock-forming minerals in limestone. As a result, groundwater found in clay-rich limestone should have higher strontium concentrations, because there is more available. In groundwater, the strontium concentration is dependent upon the initial concentration in water recharging the aquifer, precipitation, the contact time or residence time of the water, and the composition of the host-rocks through which the water flows.

Strontium 87/86 isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) are typically used in geologic investigations to determine the age of rocks and minerals from the quantities of rubidium (Rb) and strontium isotopes they contain. The dating method works from the fact that ^{87}Rb decays, with a half-life of 48.8 billion years, to ^{87}Sr . With such a large half-life, this means that all the ^{87}Rb present on earth is primordial. In addition, there are only two sources of ^{87}Sr , primordial and that which forms from the decay of ^{87}Rb . During the cooling of magma, as minerals precipitate or crystallize at different temperatures, Sr tends to become concentrated in the plagioclase minerals, leaving Rb in the liquid phase. Hence, this process of fractional crystallization results in the Rb/Sr ratio in residual magma to increase over time resulting in rocks with increasing Rb/Sr ratios with increasing differentiation. If the initial amount of Sr is known or can be extrapolated, the age of the rock can be determined by measuring the Rb and Sr concentrations and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. The ratio $^{87}\text{Sr}/^{86}\text{Sr}$ in rocks varies greatly with rock type and age. The average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for rock types range from 0.702 to 0.716 (Michener and Lajtha 2007). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of modern seawater and precipitation is about 0.7092 (Åberg et al. 1989, Capo et al. 1998). The $^{87}\text{Sr}/^{86}\text{Sr}$ of groundwater will be similar to the concentration seen in the underlying rock, so strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) are routinely use in hydrochemical studies to determine sources and mixing relationships of surface and groundwater. They have proved particularly useful in determining weathering processes and quantifying end-member mixing processes.

In this study, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio ranged from 0.7077 to 0.7083. Each of the four TLAP monitoring areas; Barton Creek West, Lost Creek, Lazy Nine, and Travis County MUD No. 4 have significantly different mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio concentrations for the baseline data. In addition, the Travis County MUD No. 4, which has two baseline sites; Rimrock Spring and North Sycamore Creek have similar strontium ratio mean concentrations for this TLAP irrigation site. This suggest that there is little variance within individual TLAP irrigation areas, but significant differences between different TLAP facilities and their associated irrigation areas. The differences seen in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between TLAP sites is contributed to differences in strontium concentrations in the underlying rocks and in the treated wastewater use for irrigated, where wastewater irrigation is occurring. The assumption is that over time the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio will increase to levels greater than 0.7082, which is about levels currently observed at Barton Creek West and Lost Creek.

The Barton Creek West TLAP does not seem functional and is allowing pollutants to pass through the system and into the receiving water at Barton Scenic Bluff Spring. The Lost Creek TLAP seems more protective than the Barton Creek West TLAP but could still be leaching excessive chloride, sodium, nitrate, and boron into the receiving water at Short Spring Branch. There are four possible scenarios that would explain these conditions. One scenario is that both TLAP irrigation fields are functioning similarly, but the effluent from the Lost Creek facility has lower concentrations of the tested parameters, thus the receiving water at Short Spring Branch is still less impacted when compared to Barton Scenic Bluff. The second scenario is that the requirements of the Lost Creek TLAP are more protective than the requirements for the Barton Creek West TLAP so that more pollutants are getting bound in the soils of the irrigation field or that more of the wastewater effluent is lost due to evapotranspiration (ET) at the Lost Creek TLAP field and not as much effluent arrives at Short Spring Branch. The third scenario is that the Lost Creek TLAP is not protective but it is located in an area with a large drainage area so that dilution is dampening the impact to the receiving water. Finally, the fourth scenario is some combination of the three other scenarios.

Currently there is no way to analyze the first scenario described above because the City of Austin Watershed Protection Department does not currently know the concentrations in the effluent applied to the irrigation fields at either TLAP facility. It is unlikely that City staff would be given permission to sample water to be irrigated onto TLAP fields and thus it may be impossible to obtain this information.

The Lost Creek facility only has 6.5 acre-feet more storage volume and is authorized to dispose of treated domestic wastewater effluent at a daily average flow approximately four times higher than the Barton Creek West facility, but the Lost Creek facility has approximately 5.8 times the amount of irrigation land to apply effluent. While each facility has roughly the same permitted application rate (2.75 at Lost Creek vs 2.65 acre-feet per year per acre at Barton Creek West) the calculated application rate using the permitted daily average flow and area of irrigation land would be lower at the Lost Creek facility (1.89 acre-feet per year per acre). It is possible that conditions present at the Lost Creek facility are more protective than conditions at the Barton Creek West facility and not as much effluent is leaching into the receiving water downgradient of the Lost Creek facility. This would coincide with the strontium 86/87 ratios being only slightly higher at Short Spring Branch when compared to the un-impacted sites. But strontium 86/87 ratios also support the theory of increased dilution at this site. It is unlikely that WPD will be able to discern which of these scenarios is most likely occurring through continued monitoring of this site.

CONCLUSIONS

Baseline mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for each TLAP monitoring area are significantly different between the facilities and do not vary significantly within each individual area.

Concentrations of chloride, nitrate/nitrite, calcium, potassium, sodium, alkalinity, and conductivity were highest at Barton Scenic Bluff Spring which is influenced by irrigation water from the Barton Creek West TLAP. The pH at this location was lower than the other sites and the rate of detection for copper and boron was higher. Chloride, nitrate, calcium, potassium, sodium, alkalinity, magnesium, and sulfate concentrations were shown to be significantly impacted by irrigating areas with reclaimed water within the Critical Water Quality Zone and/or floodplain as defined by the City of Austin Land Development Code (Porrás et al. 2016). Barton Scenic Bluff Spring did not show elevated sulfate or magnesium concentrations when compared to the Little Barton Creek or Rimrock Spring, which are not yet impacted by TLAP irrigation. When compared to the sulfate and magnesium concentrations found in the un-impacted sites for the reclaimed water study, concentrations of sulfate were higher in this study for all sites with the exception of North Sycamore Creek and the concentrations of magnesium were higher in this study at all sites.

Concentrations of chloride and sodium at Short Spring Branch were not as high as concentrations at Barton Scenic Bluff, but were higher than at the three sites not yet impacted by TLAP irrigation. Nitrate/nitrite concentrations were higher at Short Spring Branch when compared to the three sites not yet impacted by TLAP irrigation but not significantly higher. There was only one sample that contained concentrations of boron below the detection limit at Short Spring Branch which was less than the un-impacted sites but not significantly less. Receiving waters impacted by similar TLAP irrigation practices will likely experience elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios along with elevated concentrations of chloride, sodium, and nitrate/nitrite. Calcium, potassium, alkalinity, and conductivity may also be elevated due to TLAP irrigation practices.

RECOMMENDATIONS

- The drainage network at Short Spring Branch is larger and more complex than at other sites in this study. In addition, the complexity of the network is a confounding factor in inferences made about the level of protection provided by the Lost Creek TLAP. It is unlikely that WPD staff will be able to monitor all of the necessary locations to assess the Lost Creek TLAP. Thus, WPD staff recommend that Short Spring Branch be dropped from future sampling.
- Continue sampling downgradient of Barton Creek West, Lazy Nine, and Travis County MUD No. 4 facilities when the latter two facilities come online in order to analyze pre- and post-TLAP facility data. The Quality Assurance Project Plan (QAPP) shall define at what point the facilities are to be considered online and sampling should recommence.
- Relocate the North Sycamore at Foster Ranch Road monitoring site closer to and downgradient of the effluent irrigation area of Travis County MUD No.4.

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