City of Austin
Founded by Congress, Republic of Texas, 1839
Watershed Protection Department
P.O. Box 1088, Austin, Texas 78767

July 28, 2025

Laurie Gharis, Chief Clerk **VIA ELECTRONIC SUBMITTAL**
Office of the Chief Clerk
Texas Commission on Environmental Quality
P. O. Box 13087, MC-105
Austin, Texas 78711-3087

SUBJECT: Reply to the Executive Director's Response to Requests for Reconsideration
Blizexas, LLC Proposed Permit No. WQ0016111001

Dear Ms. Gharis:

By this letter, the City of Austin (City) submits its Reply to the Executive Director's Response to Requests for Reconsideration for proposed Texas Land Application Permit (TLAP) TCEQ Permit No. WQ0016111001, pursuant to 30 Texas Administrative Code §55.201(e).

The City respectfully requests reconsideration of the following issues raised in its written comments on January 19, 2024, and April 2, 2025 Request for Reconsideration (enclosed with this letter) because, as currently proposed, the TLAP would likely harm the environment in the irrigation fields and on the City's immediately adjacent Shield Ranch conservation easement, which would violate 30 TAC 309.20, 307.7, and 30 TAC 222.151.

The Executive Director's Response to Requests for Reconsideration states that the issues raised in the requests are either outside TCEQ's jurisdiction and cannot be considered as part of the wastewater permitting process, or they were considered by the ED and were [previously] addressed in the ED's Response to Comments. However, as outlined in this letter and in the City's Request for Reconsideration, there are areas lacking specificity in the ED's responses and an explanation was not provided as to why our comments were not addressed or our requests were not feasible.

The City's primary concern is focused on addressing environmental issues. Specifically, the City is concerned that the proposed TLAP could negatively impact environmentally sensitive areas and diminish the value of our adjacent conservation easement due to:

1. Inadequate monitoring of groundwater quality in the subsurface below the wastewater application site;
2. The risk of nutrient contamination, including nitrates, *Escherichia coli*, and dissolved solids, seeping into surface waters and the shallow groundwater system; and
3. The inadequacy of the storage design for a concert venue.

The Executive Director's RTC and Response to the Request for Reconsideration did not sufficiently or directly address any of the City of Austin's requests or questions. We respectfully request that

TCEQ provide clear and complete, responses to each of the City's written comments as well as a copy of the revised draft permit.

1. Monitoring of Actual Irrigation Rates: The City requested monitoring of actual irrigation rates. The ED's Response to Comments (RTC) stated that the permit includes a blanket prohibition on wastewater percolation (Special Provision 15) and requires monitoring of groundwater quality through lysimeters (Special Provision 9). However, neither provision addresses the need by the Applicant to monitor actual irrigation rates, which may vary substantially, particularly given the venue's variability in flow between peak use during concerts and dormancy on other days. The City requests the Commissioners consider an additional Special Provision requiring daily monitoring of irrigation rates and the locations of the irrigation zones being used.

2. Effluent Quality Standards: The City requested that effluent quality meet the level required for subsurface area drip dispersal systems (SADDS) with public access. The draft permit (dated June 30, 2023) proposed effluent limits of 20 mg/L BOD and 20 mg/L TSS, but these limits are insufficient for environmentally sensitive areas. The RTC states in Response 12 that the draft permit includes the more stringent effluent set of 10 mg/L BOD and 15 mg/L TSS proposed by the Applicant in their application, but an updated draft permit reflecting these limits was not provided as part of the response.

   The following protective limits paired with a superior treatment train that includes nitrogen removal via combined nitrification and denitrification, such as that in use at the Headwaters MUD permit (WQ0014587001) are recommended.

   - 5 mg/L BOD
   - 5 mg/L TSS
   - 2 mg/L NH_3-N
   - 1 mg/L TP

   The limits listed above and a reporting requirement for TN would better protect the area and the City's conservation easement. The City requests that effluent limits for similarly situated TLAP (SADDS) permits align with these more protective standards to ensure good governance, effective water management, and environmental stewardship.

   Furthermore, the City has conducted several field monitoring studies of reclaimed water irrigation systems in areas with thicker soils better suited to the attenuation of treated effluent and found detectable impacts in springs and surface waters downgradient from reclaimed irrigation areas. Reports of our findings from these studies were attached to our initial comments January 19, 2024. We request that the ED use their discretion to consider more stringent effluent limits based on these findings and in the interest of consistency with other SADDS limits in the Edwards Aquifer Contributing and Recharge zones.

3. Adequacy of Storage Design: The City requested that the Applicant or TCEQ apply a daily water balance using long-term meteorological data and the proposed operating plan for drip

irrigation to confirm the adequacy of the 3-day storage requirement in the draft permit. Given the high volumes of wastewater during peak operation associated with a concert venue and the sensitivity of this area, a larger storage capacity may be warranted. The Headwaters MUD (Permit No. WQ0014587001) includes a 7-day storage capacity requirement, which may be appropriate here.

The City emphasizes the need for additional safeguards to the permit to prioritize the protection of environmentally sensitive areas in the Barton Creek watershed and adjacent to the City's conservation easement. These measures not only ensure compliance with regulatory standards but also proactively safeguard natural resources, water quality, and endangered species habitats.

Thank you for your consideration. If you have questions, please contact me at Liz.Johnston@austintexas.gov and Kaela.Champlin@austintexas.gov.

Sincerely,

Liz Johnston
Interim Environmental Officer
Watershed Protection Department
City of Austin

Enclosure: January 29, 2024 City of Austin Comment Letter and April 2, 2025 City of Austin Request for Reconsideration

cc: Deba P. Dutta, P.E., TCEQ Municipal Permits MC-148

City of Austin
Founded by Congress, Republic of Texas, 1839
Watershed Protection Department
P.O. Box 1088, Austin, Texas 78767

April 2, 2025

Laurie Gharis, Chief Clerk
Office of the Chief Clerk
Texas Commission on Environmental Quality
P. O. Box 13087, MC-105
Austin, Texas 78711-3087

VIA ELECTRONIC SUBMITTAL

SUBJECT: Request for Reconsideration of the Executive Director's Decision and Response to Comments on Blizexas, LLC Proposed Permit No. WQ0016111001 and the Executive Director's preliminary decision on the application

Dear Ms. Gharis:

By this letter, the City of Austin (City) submits its Request for Reconsideration of the Executive Director's Decision and Response to Comments (RTC) on the application by Blizexas, LLC (Applicant) for a new Texas Land Application Permit (TLAP), TCEQ Permit No. WQ0016111001, and the Executive Director's preliminary decision on the application pursuant to 30 Texas Administrative Code §55.201(e). These comments are in addition to those previously submitted on behalf of the City of Austin on January 29, 2024, which are enclosed with this letter.

The City recently purchased a conservation easement for water quality and quantity protection in partnership with Shield Ranch on December 11, 2024, after the close of the public comment period. The property is immediately adjacent to and downgradient from the Applicant's proposed irrigation fields. Both the irrigation fields and the adjacent area, including the Shield Ranch property where the City's conservation easement is located, are environmentally sensitive areas where the City is actively working to protect water quality and endangered species. Additionally, the City owns property and other conservation easements in the Barton Creek watershed. These properties are also environmentally sensitive areas that provide habitat for migratory songbirds, including the federally-protected Golden-cheeked warbler, and protect water quality and quantity in the Barton Creek watershed and the Edwards Aquifer.

The City respectfully requests reconsideration of the following issues raised in its January 19, 2024 written comments because the TLAP as proposed would likely harm the environment in the irrigation fields and on the City's conservation easement, violating 30 TAC 309.20, 307.7, and 30 TAC 222.151.

The City's primary concerns focus on addressing environmental issues and ensuring regulatory compliance. Specifically, the City is concerned that the proposed TLAP could negatively impact environmentally sensitive areas and diminish the value of our adjacent conservation easement due to:

1. Inadequate monitoring of groundwater quality below the wastewater application site; and

2. The risk of nutrient contamination, including nitrates, Escherichia coli, and dissolved solids, seeping into surface waters and the shallow groundwater system.

The following three comments are specific examples, but many instances of comments from the City's January 19, 2024 written comments were not adequately or directly addressed in the Executive Director's RTC. We respectfully request that the TCEQ provide clear and complete, point-by-point responses to all of the City's written comments as well as a copy of the revised draft permit.

1. Monitoring of Actual Irrigation Rates: The City requested monitoring of actual irrigation rates. The TCEQ responded that the permit includes a blanket prohibition on wastewater percolation (Special Provision 15) and requires monitoring of groundwater quality through lysimeters (Special Provision 9). However, neither provision addresses the need to monitor actual irrigation rates, particularly given the venue's variability in flow between peak use during concerts and dormancy on other days. The City requests an additional Special Provision requiring daily monitoring of irrigation rates and the locations of the irrigation zones being used.

2. Effluent Quality Standards: The City requested that effluent quality meet the level required for subsurface area drip dispersal systems (SADDS) with public access. The draft permit (dated June 30, 2023) proposed effluent limits of 20 mg/L BOD and 20 mg/L TSS, but these limits are insufficient for environmentally sensitive areas and fail to meet statewide requirements under 30 TAC 309.4. The RTC states in Response 12 that the draft permit includes the more stringent effluent set of 10 mg/L BOD and 15 mg/L TSS proposed by the Applicant in their application, but an updated draft permit reflecting these limits was not provided as part of the response. More protective limits paired with a superior treatment train that includes nitrogen removal via combined nitrification and denitrification, such as that in use at the Headwaters MUD permit (WQ0014587001):

    - 5 mg/L BOD
    - 5 mg/L TSS
    - 2 mg/L NH_3-N
    - 1 mg/L TP
    - and a reporting requirement for TN would better protect the area and the City's conservation easement. The City requests that effluent limits for similarly situated TLAP (SADDS) permits align with these more protective standards to ensure effective water management and environmental stewardship.

   Furthermore, the City has conducted several field monitoring studies of reclaimed water irrigation systems in areas with thicker soils better suited to the attenuation of treated effluent and found detectable impacts in springs and surface waters downgradient from reclaimed irrigation areas. Reports of our findings from these studies were attached to our initial comments January 19, 2024. We request that the Executive Director use their discretion to consider more stringent effluent limits based on these findings and in the interest of consistency with other SADDS limits in the Edwards Aquifer Contributing and Recharge zones.

3. Adequacy of Storage Design: The City requested that the Applicant or TCEQ apply a daily water balance using long-term meteorological data and the proposed operating plan for drip irrigation to confirm the adequacy of the 3-day storage requirement in the draft permit. Given the high volumes of wastewater during peak operation associated with a concert venue and the sensitivity of this area, we believe a larger storage capacity may be warranted. The Headwaters MUD permit includes a 7-day storage capacity requirement.

The City emphasizes the need for discretion and due diligence from the Executive Director to prioritize the protection of environmentally sensitive areas in the Barton Creek watershed and adjacent to the Shield Ranch conservation easement. These measures not only ensure compliance with regulatory standards but also proactively safeguard natural resources, water quality, and endangered species habitats.

The City also notes that staff were given insufficient time to review the RTC as we did not receive the response until March 10, 2025. The City requests additional time to determine if we wish to seek a contested case hearing.

Thank you for your consideration. If you have questions, please contact me at Liz.Johnston@austintexas.gov and Kaela.Champlin@austintexas.gov.

Sincerely,

Liz Johnston
Interim Environmental Officer
Watershed Protection Department
City of Austin

Enclosure: January 29, 2024 City of Austin Comment Letter

cc: Deba P. Dutta, P.E., TCEQ Municipal Permits MC-148

City of Austin
Founded by Congress, Republic of Texas, 1839
Watershed Protection Department
P.O. Box 1088, Austin, Texas 78767

January 29, 2024

Laurie Gharis, Chief Clerk
Office of the Chief Clerk
Texas Commission on Environmental Quality
P. O. Box 13087, MC-105
Austin, Texas 78711-3087

VIA ELECTRONIC SUBMITTAL

SUBJECT: Submittal of Written Comments
Blizexas LLC - Rockingwall Ranch Proposed Permit No. WQ0016111001

Dear Ms. Gharis:

By this letter, the City of Austin (City) submits its written public comments regarding the application of Blizexas LLC for a new Texas Land Application Permit (TLAP), and Draft Permit No. WQ0016111001. The City submits these comments because the environmental sensitivity of the area subject to this permit is not adequately addressed in the application and draft permit. This letter also provides information on the potential impacts to water quality in similar settings for use by TCEQ in modifying the draft permit. Although a discharge permit is clearly not appropriate for this area, and a subsurface area drip dispersal system (SADDS) may be the best alternative, many improvements to the draft permit can be made to protect water quality. The City can be reached by mailing correspondence to my address on this letterhead and by telephone to my direct number, (512) 974- 2212.

The area to be used for land application of treated municipal wastewater covered by the proposed TLAP, Permit No. WQ0016111001 is in the Edwards Aquifer Contributing Zone and has the potential to impact surface waters if partially treated effluent is released to shallow groundwater seeps and springs in tributaries. Specifically, the SADDS areas likely drain into tributaries of Barton Creek upstream from the Barton Springs Segment of the Edwards Aquifer. The City has conducted several field monitoring studies of similar systems in areas with thicker soils better suited to the attenuation of treated effluent and found detectable impacts in springs and surface waters downgradient from reclaimed irrigation areas. We have attached reports of these studies for your review (Attachment 1 – Reclaimed water irrigation water quality impact assessments). Of primary concern are nutrient impacts to algae growth in these surface waters. The City has also conducted gain/loss studies in Barton Creek downstream from the proposed permit. These indicate that the reaches downstream are gaining flow from shallow groundwater discharge which could be hydrologically connected to the SADDS areas. Our recent report describing these findings is attached (Attachment 2 – Upper Barton Creek Gain/Loss Study at Shield Ranch). The combined weight of evidence calls for more stringent permit requirements in these sensitive areas.

The City requests the following points of concern be addressed in the updated draft permit and mitigation practices defined and implemented prior to initiation of wastewater effluent irrigation. With these improvements and attention to operation and maintenance, discharges to the groundwater system and surface waters can be minimized. Additionally, we would like to work with the applicant and TCEQ to design a monitoring plan for the site that would provide data on the impacts to water quality downstream from ongoing operation of the facility. The monitoring lysimeters proposed in the application are a good start, but additional monitoring is warranted. There is currently limited monitoring data available for SADDS systems in marginal soils in the Barton Springs Zone.

We would appreciate the opportunity to review the revised draft permit with TCEQ responses to comments incorporated.

A. Soils

Comment: Soils in the drip dispersal areas are Brackett - Rock outcrop - Comfort complex BtD and Doss silty clay DoC as shown in the application. The Comfort soils are a shallow complex of extremely stony clay and gravelly clay and gravelly clay loam over limestone bedrock. These soils have severe limitations for treatment or disposal of wastewater effluent. The Brackett Soils in the proposed irrigation areas also have severe limitations for sanitary facilities and water management of shallow depth to rock, large stones, and slow percolation. The Doss soils have limitations for shallow depth to bedrock, shallow rooting zones, and slow percolation (USDA soil survey for Hays County). In the permit application all dispersal drip field soils are represented by one composite sample for each depth fraction. Given that these soils are likely to be very heterogenous, further sampling is warranted. All these conditions combined with the sensitivity of the watershed require attention to design and construction of the dispersal system beyond what is required in other areas of the state where the natural soils are more suitable for nutrient uptake.

Recommended Changes:

- Require maintenance of a 12-inch minimum soil depth of suitable soils below the dispersal system to sustain a viable root zone, support crop growth and maximize uptake of wastewater effluent and nutrients.
- Require monitoring of actual irrigation application rates adequate for uptake of wastewater effluent andnutrients, such that percolation below the root zone does not occur.
- Eliminate bedrock outcrop areas from total irrigation acreage. Determine if remaining areas are adequate to meet the required application rate.
- Imported soils will likely be necessary to reach the specified vertical separation distances below and above the drip dispersal system. Built drawings indicating where soil is added should be included as a permit requirement.
- Periodic reevaluation of the soil depth and quality over time should be incorporated into special conditions in the permit.

B. Geology

Comment: The Upper Glen Rose Limestone is present at the surface on-site and throughout the area, including in the channel of nearby Barton Creek. The Glen Rose consists of hard limestone alternating with more marly beds which weather to form a characteristic stair-step topographic profile on hills. While not as aggressively weathered as the overlying and more well-known Edwards Group, the Glen Rose has substantial karst development and hosts the Trinity Aquifer which provides water to thousands of people in Central Texas in addition to supplying the springs that sustain baseflow in Upper Barton Creek and its tributaries in this area. The Groundwater Quality Report submitted with the permit application noted impacts to wells were unlikely but did not mention potential impacts to nearby springs. The tributary to Barton Creek located directly north of the SADDS areas had measurable flow into Barton Creek in June and July of 2019 (Sydow et al. 2024).

Recommended Change:

- Inspect, review, and evaluate surface and subsurface rock features prior to installation of drip irrigation system and construction of treatment facilities, storage pond, and all underground utilities.

C. Treatment Plant and Effluent Limits

Comment: The treatment system is proposed to be a conventional activated sludge plant including flow equalization, bar screens, an aeration basin, final clarifier, a tertiary media filter and chlorine contact chamber. The application stated that the plant is capable of effluent limits of 10 mg/L BOD 15 mg/L TSS (TCEQ-10054 pg 25 of 80). In addition, the design criteria used in calculations indicates the plant will be capable of an effluent limit of 10 mg/L TSS (TCEQ-10054 Attachment 14). However, the draft permit is written for less stringent limits of 20 mg/L BOD and 20 mg/L TSS (Draft WQ0016111001 pg 2). The subsurface area drip dispersal system would operate better at the designed effluent of 10 mg/L BOD and 10 mg/L TSS with fewer soil clogging and maintenance problems than the draft permit of 20 mg/L BOD and 20 mg/L TSS. Although this limit may be appropriate in other parts of the state, more stringent limits would be warranted in this sensitive area with the noted soil limitations. We would recommend that the design criteria be used as the effluent limits. We would also recommend that modifications be considered to the plant to maximize the nutrient removal capabilities. Low cost and operational changes to conventional activated sludge treatment should be considered such as those recommended in Water Research Foundation Project No. 4973 (Neethling, Falk, and Evans, 2023).

D. Effluent Irrigation and Management Plan

Comment: While the default effluent application rate of 0.1 gpd/ft^2 appears to be low enough on an annual basis, and the vegetative cover is capable of necessary nutrient uptake, no storage or water balance calculations are required for SADDS systems. Given the sensitivity of the area and the improvements in hydrological and water quality models over the years since the SADDS rules were written, it would be warranted to spend more time evaluating the actual performance of the system. Like spray irrigation, a daily water balance using long-term hydrological data would provide some confidence that no discharges could be expected. Alternately, any unit area models such as GLEAMS or watershed models such as SWAT could be used to do the same accounting. Even if it is not appropriate for the applicant to provide this, the TCEQ could incorporate such models into their review process.

Comment: On Attachment 8 – Buffer Zone Map, the Wastewater Treatment Plant is identified as the boundary of all units. The150 ft buffer indicated is not from the treatment units, each treatment unit is not shown, and the distance from each treatment unit to the property boundaries is not shown as required in Section 3. A. TCEQ-10053 (10/31/2022 Page 17 of 24). A minor detail given is that the buffer meets requirements, but the figure does not meet the language of the permit application.

Recommended Changes:

- Log actual water balance daily with application/storage records to determine that irrigation rates do not exceed evapotranspiration (ET) rates of cover crop.
- Verify adequacy of 3-day storage volume provided in the storage pond and account for seasonal differences during cool and rainy seasons through use of long-term hydrological data and a water balance for the SADDS system.

- Determine location and installation of additional soil moisture sensors to determine areas of soil saturation. Evaluate performance of such sensors over time.
- For each phase of development, establish 100% of design vegetation cover for that area prior to initiation of irrigation.
- Determine mitigation measures to eliminate presence and development of preferential flow percolating into shallow groundwater systems.

In summary, effluent irrigation on lands in the sensitive Barton Springs Contributing Zone, especially so close to Barton Creek, should be undertaken carefully and in a manner that fully protects surface waters and recharge to the Edwards Aquifer. TCEQ's draft permit should include additional permit provisions requiring modifications to the proposed design and operations of the irrigation system to protect the water resources at risk.

If you have questions, please contact me at (512) 974-2212.

Sincerely,

Katie Coyne
Environmental Officer
Watershed Protection Department
City of Austin

<u>References</u>

Clamann, A, and S Hiers, A Richter, M Scoggins, C Herrington. 2014. Reclaimed water irrigation water quality impact assessment, Phase 1 Summary of Results. City of Austin Watershed Protection Department. DR-15-03. 17 p.

Neethling, J and M Falk, E Evans. 2023. Guidelines for Optimizing Nutrient Removal Plant Performance. HDR, Inc. for The Water Research Foundation. Project No. 4973. 613 p.

Porras, A, and A Richter, A Claman, S Hiers, M Scoggins, C Herrington, W Burdick, S Sudduth. 2016. Reclaimed water irrigation water quality impact assessment. City of Austin Watershed Protection Department. SR-16-06. 50 p.

Richter, A, and S Hiers. 2017. Comparison of water quality at locations currently receiving wastewater effluent irrigation to locations planned for future wastewater effluent irrigation. City of Austin Watershed Protection Department. DR-18-01. 18 p.

Sydow, L. and S Zappitello, K Parker, A Guidry. 2024. Upper Barton Creek Gain/Loss Study at Shield Ranch. City of Austin Watershed Protection Department. RR-24-01. 20 p.

cc:
Jorge L. Morales, P.E., CFM, WPD Director
Firoj Vahora, TCEQ Municipal Permits MC-148

Attachment 1

Reclaimed water irrigation water quality impact assessments

Reclaimed water irrigation water quality impact assessment, Phase 1 Summary of Results

DR-15-03; December 2014

Andrew Clamann, Scott Hiers P.G., Aaron Richter E,I,T,, Mateo Scoggins and Chris Herrington, P.E..

City of Austin
Watershed Protection Department
Environmental Resource Management Division

Introduction

Watershed Protection Department staff collected water samples to enable evaluation of the potential water quality impacts on surface and ground water resources from the irrigation of reclaimed water provided by City of Austin wastewater treatment facilities within the critical water quality zone and floodplain as defined by the City of Austin Land Development Code. Reclaimed water irrigation adjacent to creeks may migrate to shallow groundwater and into creeks through subsurface water flow, may be irrigated directly into creeks during improper spray application, or may load constituents into riparian soils that exceed natural assimilative capacities and thus be transported to creeks during runoff events. The following is a summary of the results of initial sampling from on-site reclaimed water, surface water, ground water and periphyton. Preliminary conclusions based on these initial results are provided at the end of this summary data report.

This project was designed with two phases. Phase one sampling was a one-time evaluation of upstream and downstream conditions relative to on-site reclaimed water and local spring discharge. Sampling for phase two will be determined based on the results of phase one and includes repeated follow-up sampling to illuminate spatial and temporal variability and to allow application of robust statistical analysis methods.

Methods

The field investigation was conducted on October 15, 2014. Physiochemical parameters were collected in the field using a multiprobe water quality meter, and spring and stream discharge was measured with a Marsh McBirney Flowmate. Water samples from reclaimed water sources (irrigation lines and ponds), surface water (streams), groundwater (spring discharge) and periphyton (from rock scrapings) were collected by WPD staff and delivered to the Lower Colorado River Authority laboratory for analysis following City of Austin standard operating procedures.

In the first phase of this study 21 sites within one park and three golf courses with recent application of reclaimed water were sampled (Table 1, Figure 1). Sites included four known springs (10765, 661, 662, and 10769), on-site reclaimed water irrigation source ponds or supply lines (10767, 10775, 10779, and 10768), and upstream/downstream sample sites on creeks (3858/10767, 10773/625, 3879/10778, 10770/10772, and 843/10771).

Table 1. Sites sampled during phase 1.

Location	Site number and name	Purpose
Bartholomew Park	3858 Tannehill Creek @ Berkman Dr	upstream of irrigation
	10766 Tannehill downstream of Bartholomew Spring	downstream of irrigation
	10767 Bartholomew Park Irrigation water	source water for irrigation
	10765 Bartholomew Spring	groundwater spring
Hancock Golf Course	10773 Waller Creek @ 45th	upstream of irrigation
	625 Waller Creek @ 38th	downstream of irrigation
	10775 Hancock Irrigation Water	source water for irrigation
Morris Williams Golf Course	843 Tannehill @ Lovell	upstream of irrigation area (mainstem of Tannehill)
	10771 Tannehill @ MLK	downstream of irrigation area (mainstem of Tannehill)
	10770 Morris Williams Central Trib upstream	upstream of irrigation area (tributary of Tannehill)
	10772 Morris Williams Central Trib downstream	downstream of irrigation area (tributary of Tannehill)
	10768 Morris Williams Irrigation Pond	source water for irrigation
	10769 Moose Lodge Spring	groundwater spring
Jimmy Clay/Roy Kizer Golf Course	10776 Williamson downstream Pleasant Valley	upstream of irrigation
	3879 Williamson Creek at Dove Springs Park	upstream of spring
	661 Roy Kizer Spring	groundwater spring
	10778 Williamson downstream Roy Kizer Spring	downstream of spring
	10779 Roy Kizer Reclaim Water Pond	source water for irrigation
	65 Onion Creek at William Cannon	upstream of irrigation area
	253 Onion Creek at McKinney Falls upper pool	downstream of irrigation area
	662 Driving Range Spring	groundwater spring

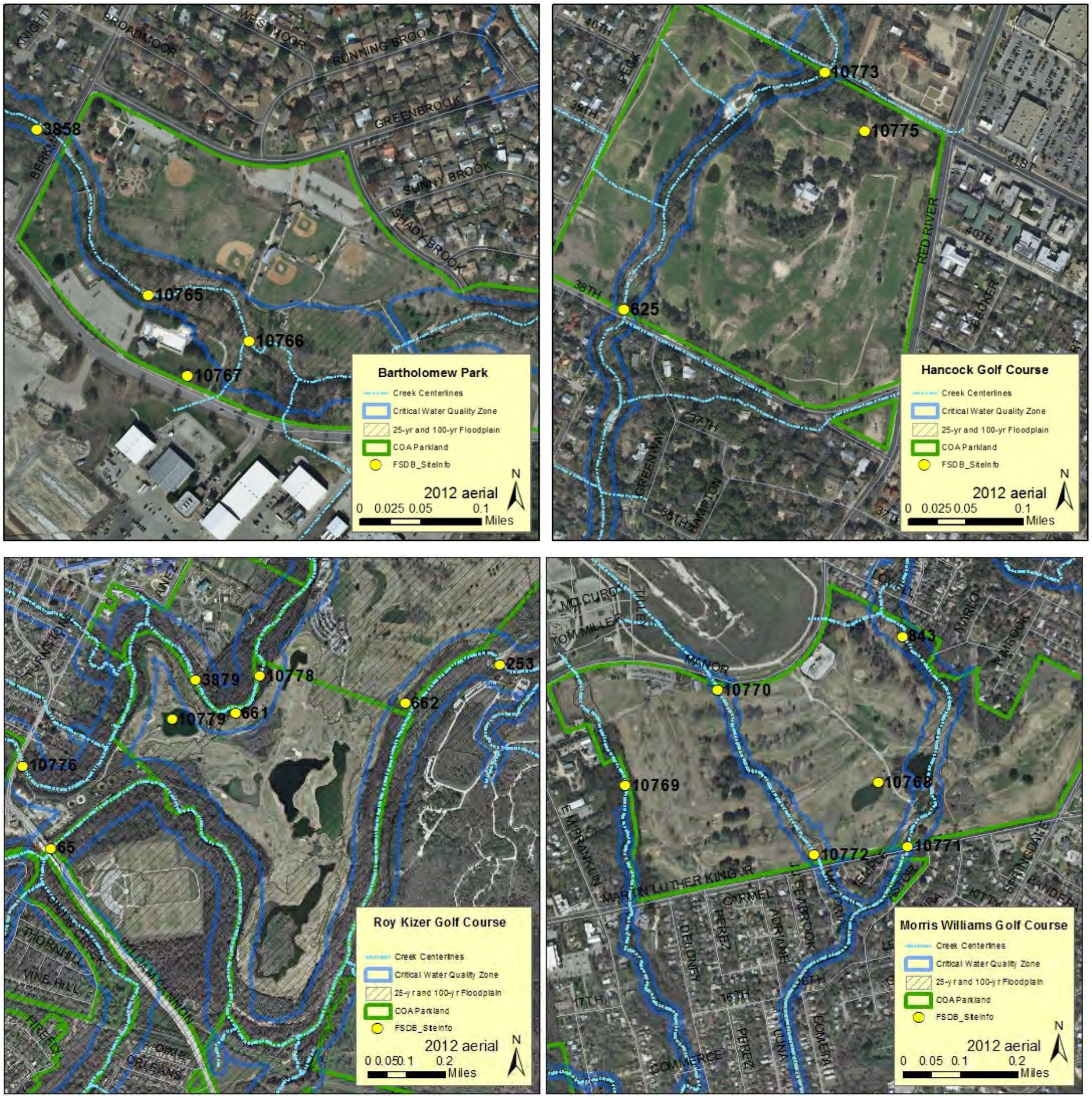

Figure 1. City of Austin parks and golf courses and sample locations selected to determine potential for impacts to surface and spring water.

Data for the following parameters were collected in water samples:

<u>Field Parameters</u>

- Conductivity
- Dissolved Oxygen
- Temperature
- pH
- Discharge (flow)

<u>Ions</u>

- Chloride
- Flouride
- Calcium
- Magnesium
- Sodium
- Potassium
- Sulfate
- Calcium Carbonate (Alkalinity)
- Strontium

<u>Nutrients and Organic Carbon</u>

- Nitrogen, Nitrate & Nitrite (as N)
- Ammonia, Total (as N)
- Total Kjeldahl Nitrogen (as N)
- Phosphorus, Total (as P)
- Orthophosphorus Total (as P)
- Total Organic Carbon (TOC)

<u>Stable Isotopes</u>

- Nitrogen-15/Nitrogen-14 Ratio
- Oxygen-18/Oxygen-16 Ratio

In addition to water samples, periphyton scrapings from rocks (epilithon) were collected from randomly selected rocks within the riffles upstream and downstream of each irrigation site. Pursuant to City of Austin Standard Operating Procedures, rocks were collected from undisturbed areas in the riffle before other sampling had occurred. Rocks chosen were relatively flat to ensure a consistent sample area. An area of 47 cm^2 was scraped from each rock and placed into a shallow collecting pan. Each rock was rinsed with deionized water to flush epilithon from the rock. Material from nine rocks in each riffle was composited in the collection pan and then placed into one darkened sample bottle and one sample bottle with H_2SO_4 for preservation. Samples were analyzed for chlorophyll *a* (opaque bottle), total organic carbon, total phosphorus, ammonia, nitrate plus nitrite, and Total Kjeldahl Nitrogen (acidified bottle).

Results and Discussion

The only site that was dry at the time of the investigation was Williamson at Pleasant Valley (site 10776), which was intended to represent upstream conditions for the segment of Williamson creek at Roy Kizer Golf Course. Williamson Creek surface flow at the time of this investigation originated near the Roy Kizer Golf Course, but an accurate total stream discharge was difficult to measure due to a portion of the discharge flowing through the cobble and gravel alluvial substrate. The next available site with measurable flow to represent upstream conditions was Williamson at Dove Springs (site 3879). Although Williamson at Dove Springs was used to represent upstream conditions for Williamson Creek, it may already have been impacted by migration of reclaimed water effluent from the golf course.

Reclaimed Water Characterization

Reclaimed water holding ponds were sampled at the Morris Williams and Roy Kizer golf courses, and samples were collected directly from reclaimed water irrigation supply lines at Hancock Golf Course and Bartholomew Park (Table 2). Concentrations of nutrients are reduced in the ponds relative to the direct irrigation supply line samples. Ion concentrations in the Roy Kizer storage pond are anomalous with respect to the other samples and long-term Walnut Creek WWTP averages.

Table 2. Results (mg/L) from reclaimed water supplies versus average (2007-2009) Walnut Creek Wastewater Treatment Plant effluent. Total nitrogen is calculated from constituents, and cannot be completely estimated in Walnut Creek WWTP effluent because organic nitrogen data is missing.

Parameter	Bartholo-mew	Hancock	Morris Williams Pond	Roy Kizer Pond	Walnut Creek WWTP Effluent	
					average	stdev
Alkalinity as CaCO3	31.2	38.2	33.4	110	35.33	23.43
Ammonia as N	0.812	0.774	0.043	0.0436	0.28	0.62
Calcium	45.8	45	42.8	35.7	38.23	6.35
Chloride	113	113	119	108	90.83	18.09
Conductivity	1082	1137	1058	827.6	.	.
Dissolved Oxygen	7.83	5.14	16.67	13.49	7.59	0.69
Fluoride	1.75	1.78	1.59	1.32	1.93	0.63
Magnesium	28	26.9	29.3	26.7	17.29	1.43
Nitrate+Nitrite as N	25.5	28.5	14.9	16	20.42	3.76
Orthophosphorus as P	4.51	4.71	0.631	1.08	4.45	1.18
pH	6.83	6.48	9.98	9.75	6.70	0.34
Phosphorus as P	4.62	4.53	1.36	1.44	4.49	1.17
Potassium	15	14.3	15.9	15.7	.	.
Sodium	117	112	122	82.5	76.82	9.19
Strontium	0.265	0.258	0.248	0.179	0.28	.
Sulfate	180	191	181	63.7	90.75	20.42
Total Kjeldahl Nitrogen as N	1.28	0.882	1.68	1.98	.	.
Total Nitrogen as N	26.78	29.38	16.58	17.98	>20.70	.

<u>Discharge</u>

Stream discharge was present at the upstream end of the central tributary on the Morris Williams Golf Course. However, due to the low flow (estimated <0.001 ft^3/s) it was not measured. Flow at all other sites was present during the sample event (Figure 2). Although some stream reaches were gaining flow while others were losing flow, the available baseflow enabled upstream/downstream comparisons. Bank seeps were observed in gaining stream reaches at Morris Williams Golf Course. Direct discharge of reclaimed water was observed to a biofiltration stormwater control and thence to Tannehill Creek at Bartholomew Park. The losing nature of some of these stream reaches may be due to subsurface flow thru alluvial substrate.

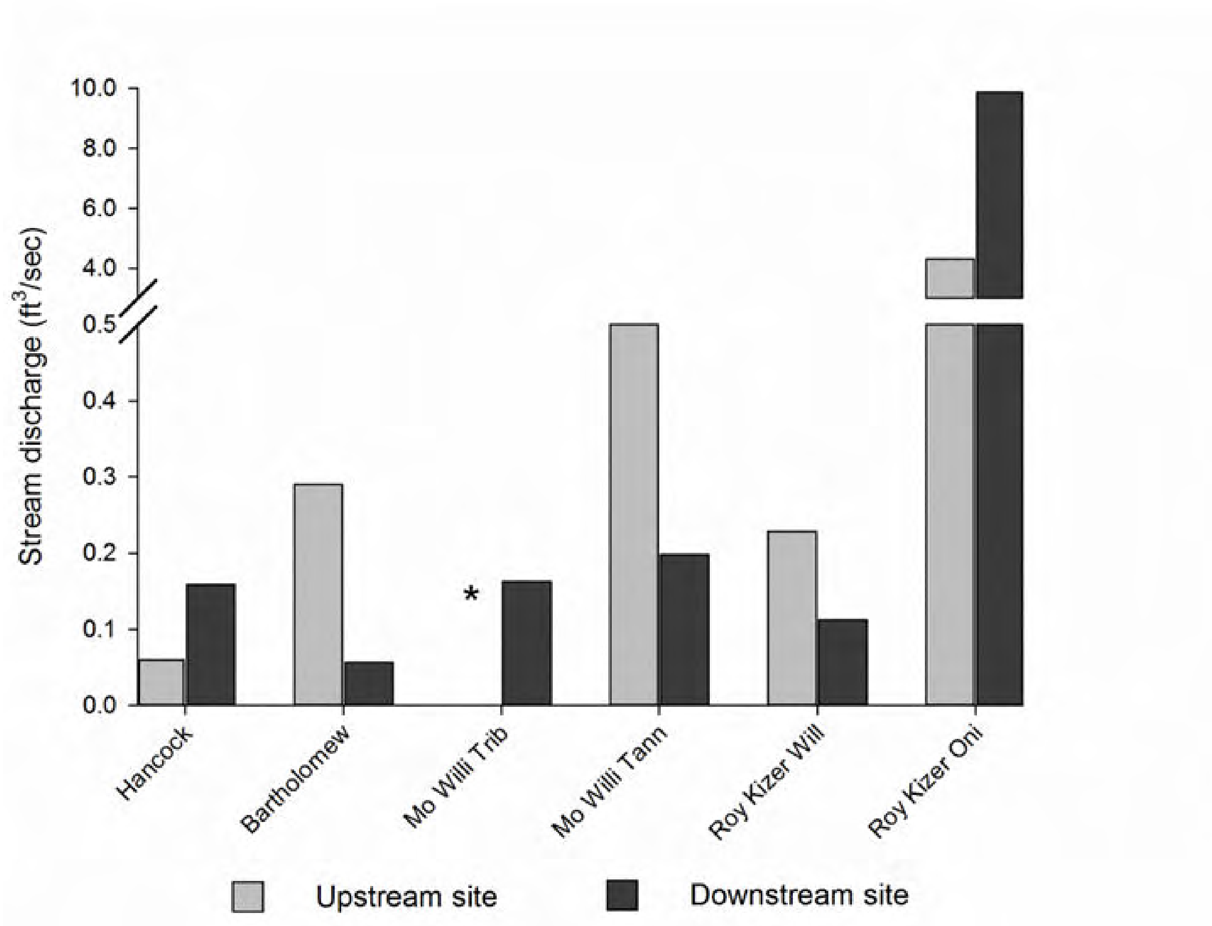

Figure 2. Stream discharge at upstream and downstream sample sites. See maps in Figure 1 for spatial orientation of upstream and downstream study sites. *Upstream site at Morris Williams Central Tributary was flowing, but was <0.001 cfs.

Conductivity

Conductivity was higher at downstream sites compared to upstream sites in 4 of 6 pairs (Figure 3). The difference in conductivity was larger between the upstream/downstream sites of the three creeks with low flow on bedrock stream substrate (i.e. Bartholomew, Morris Williams Tributary, Roy Kizer Williamson). Conductivity differences between upstream/downstream pairs were minor on larger creeks (i.e. Hancock Waller and Roy Kizer Onion) where higher baseflow could dilute the influence of reclaimed water or baseflow was largely subsurface thru alluvial substrates.

Average conductivity of upstream sites was 450 µS/cm (range 279 – 841 µS/cm)while the average conductivity of downstream sites was 565 µS/cm, which is an increase of 25%. Elevation of the specific conductance in the baseflow of a stream would be expected if there were contributions from reclaimed wastewater since reclaimed water samples indicated a much higher average conductivity (1,026 µS/cm).

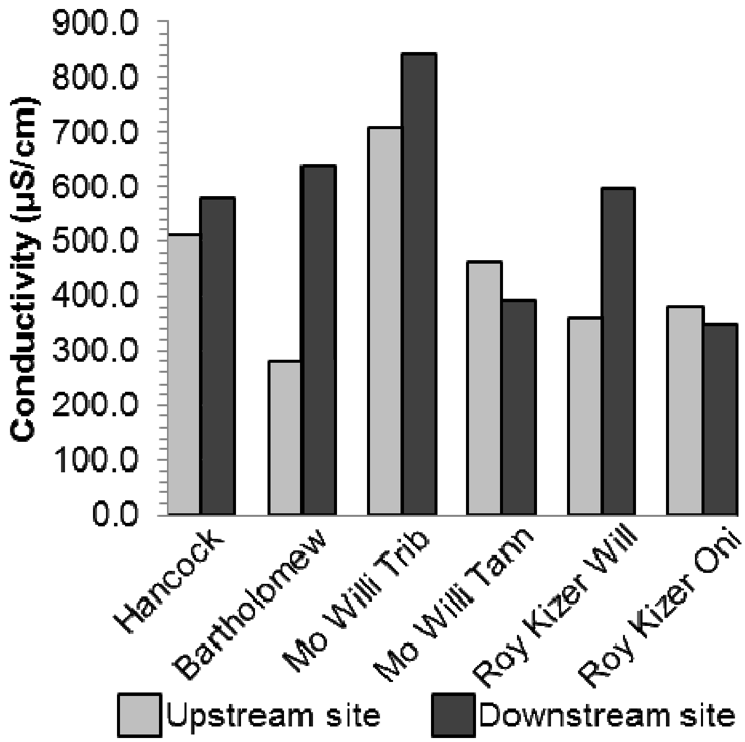

Figure 3. Conductivity values at upstream and downstream sample sites.

Chloride and Fluoride

Chloride and fluoride can be used to detect influence of municipal treated water or wastewater on surface and ground water in Austin.

A comparison of fluoride concentrations from upstream and downstream sites in the study area shows that most (4/6) sites have higher concentration in downstream samples compared to upstream samples (Figure 4A). The average fluoride concentration in reclaimed water was 1.61 mg/L, and Austin Water maintains fluoride concentrations in finished drinking water with a control range of 0.6 to 0.8 mg/L. As would be expected, differences are less evident in stream segments on the mainstem of large creeks such as Waller and Onion whose higher baseflow and urban influences obscure or dilute potential. Average fluoride concentration for all upstream sites was 0.25 mg/L while the average concentration for all downstream sites was 0.28 mg/L.

More prominent differences were observed in the comparison of chloride results from upstream to downstream relative to fluoride concentrations. Sample results show that most sites (5/6) have a higher concentration in downstream samples (Figure 4B). Average chloride concentration in reclaimed water was 113 mg/L. Average chloride concentration for all upstream sites was 20 mg/L while average concentration for all downstream sites was 42 mg/L.

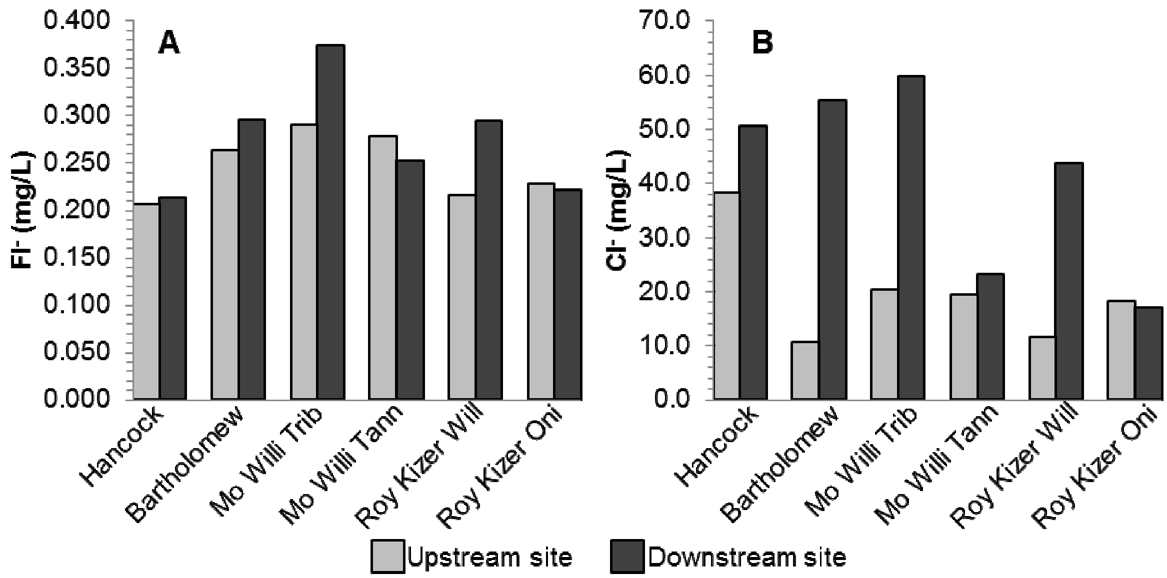

Figure 4. Fluoride (A) and chloride (B) concentrations at upstream and downstream sample sites.

Because chloride and conductivity are generally conservative in surface water, a simple mass balance calculation utilizing the concentrations of upstream, downstream and reclaimed water sites can be made to estimate the maximum potential ratio of reclaimed water exfiltrating from soils into creeks relative to upstream flow (Table 3). This calculation assumes that the difference between upstream and downstream concentrations would only be a result of reclaimed water addition to the adjacent creek. This mass balance analysis suggests the highest potential influence of reclaimed water on adjacent creeks occurs in Bartholomew Park, the Central Tributary to Tannehill in Morris Williams Golf Course, and in Williamson Creek adjacent to Jimmy Clay/Roy Kizer Golf Course.

Table 3. Ratio of the maximum potential reclaimed water exfiltration to streams relative to upstream surface water discharge estimated by simple mass balance. Negative ratios occur when downstream concentrations exceed upstream concentrations.

Parameter	Bartholomew	Hancock	MorrisWilliams (Tannehill mainstem)	MorrisWilliams (Tannehill Central Tributary)	Onion	Williamson
Conductivity	0.81	0.12	-0.10	0.61	-0.07	1.02
Chloride	0.78	0.20	0.04	0.67	-0.01	0.50

Additional Ions

In addition to physiochemical and chloride/fluoride concentrations, a suite of cation and anion parameters were evaluated to determine if surface water impacts are occurring within the study area (Figure 5A-F). As shown in Figure 5, most of the downstream sites were higher in concentration than the upstream sites for all ions. Of the total 36 upstream/downstream comparisons, the downstream site was higher in ion concentration than the upstream site in 28 instances. Although the Hancock sites did not show much difference, some increased downstream concentrations were evident. For all six ions compared at Bartholomew Park, ion concentration of downstream sites increased between 2-4 times that of upstream sites. Of note, the central tributary of Morris Williams Golf Course (Figure 5F, Mo Willi Trib) saw an eight-fold increase in sulfate.

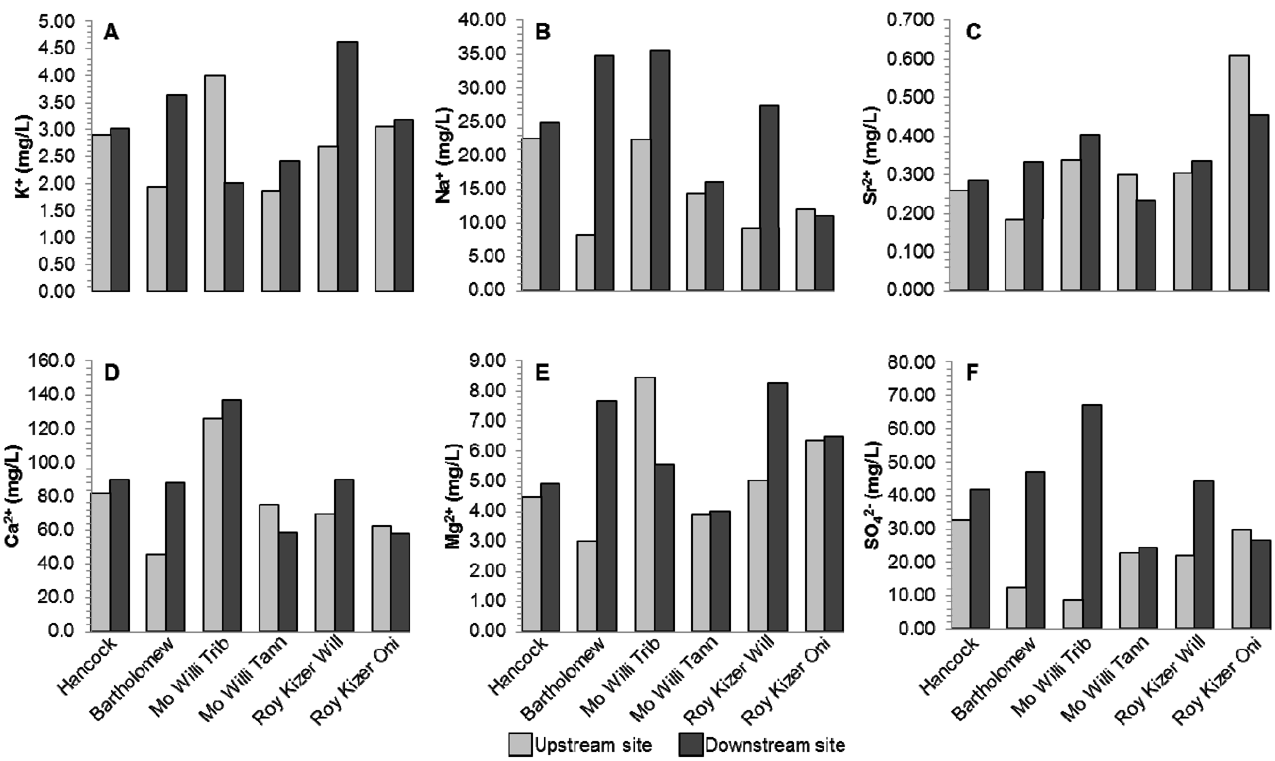

Figure 5. Potassium (A), sodium (B), strontium (C), calcium (D), magnesium (E), and sulfate (F) concentrations at upstream and downstream sample sites.

Analysis of groundwater (spring discharge) indicates similar results to surface water. Characterization of groundwater typically includes examining the cation and anion concentrations to determined hydrochemical facies of the groundwater system. The standard ions used are Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, and Cl^-. The trilinear graph or "piper plot" is the standard method for presenting the cation and anion data. Each apex of a triangle represents 100% of one or two ion constituents, with the cations represented at the lower left triangle and anions at the lower right triangle (Figure 6). The diamond-shape area between the two triangles is used to project a point that represents both the cation and anion concentrations. The advantage of the piper diagram is that a large number of samples with multiple parameters can be plotted to reveal trends with minimal confusion. The effects of mixing water from two different sources can become apparent. The mixing of two different waters will result in a plot in which unimpacted waters will be separated from pollution sources, and the impacted waters will form an intermediate line in between.

The ion data for the reclaimed water results is shown in the piper plot (Figure 6). Reclaimed water (from irrigation lines and ponds) is clearly distinct in its characterization within the plot on the right hand sides (pink squares) while the upstream, or unimpacted sites (open triangles) are clustered on the left hand side. The downstream sites (grey triangles) migrate in the direction of the reclaimed water characterization. The linear drift in the ion data towards the ion composition measured for reclaimed water indicates the mixing of sodium, chloride and sulfate enriched reclaimed irrigation water with both the background groundwater and surface water.

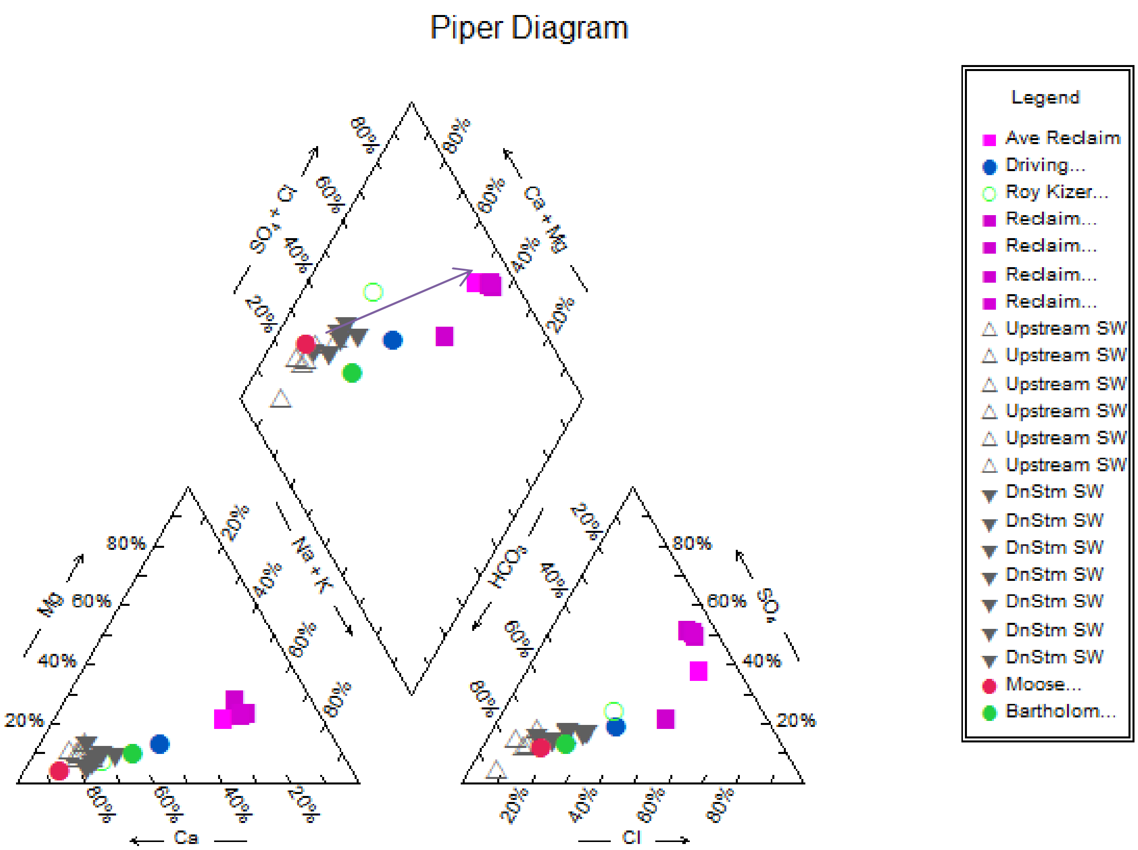

Figure 6: Piper diagram of major cation and anion data.

<u>Nutrients</u>
Excess nutrients in surface water can result in nuisance algal blooms that cause swings in dissolved oxygen concentrations, aquatic life community imbalance, odor problems and fish kills (Wharfe et al. 1984; Biggs 1985; Biggs and Price 1987; Welch et al. 1988; Quinn and Gilliland 1989; Quinn and Hickey 1990). Nutrient concentrations were higher at the majority of the downstream sites compared to the upstream sites (Figure 7A-F), especially as shown by nitrate/nitrite concentrations (Figure 7D). The increase in nutrient concentrations is most evident at Bartholomew Park and at Morris Williams Golf Course. Of note, the nitrate/nitrite concentration at the downstream site was 55 times higher than the

upstream site at both Bartholomew Park and Williamson Creek sites associated with Roy Kizer Golf Course. The average nitrate/nitrite concentration at upstream sites was 0.32 mg/L while the average downstream concentration was 1.15mg/L (total range 0.02 – 2.00 mg/L). Similarly, an increase in phosphorus (both orthophosphorus and total phosphorus) concentration is seen between upstream and downstream at four of the six monitoring sites (Figure 7E). Increases in nutrients at Morris Williams Golf Course and Bartholomew park were particularly noticeable. All of the nutrient parameters (TN, TKN, NH3, NO2+NO3, TP and OP) evaluated on Morris Williams Golf Course Tannehill sites (see Mo Willi Tann below), were between two to twenty-five times higher at the downstream sites than at the upstream sites. All nutrient parameters were higher at the downstream sites of Bartholomew Park as well.

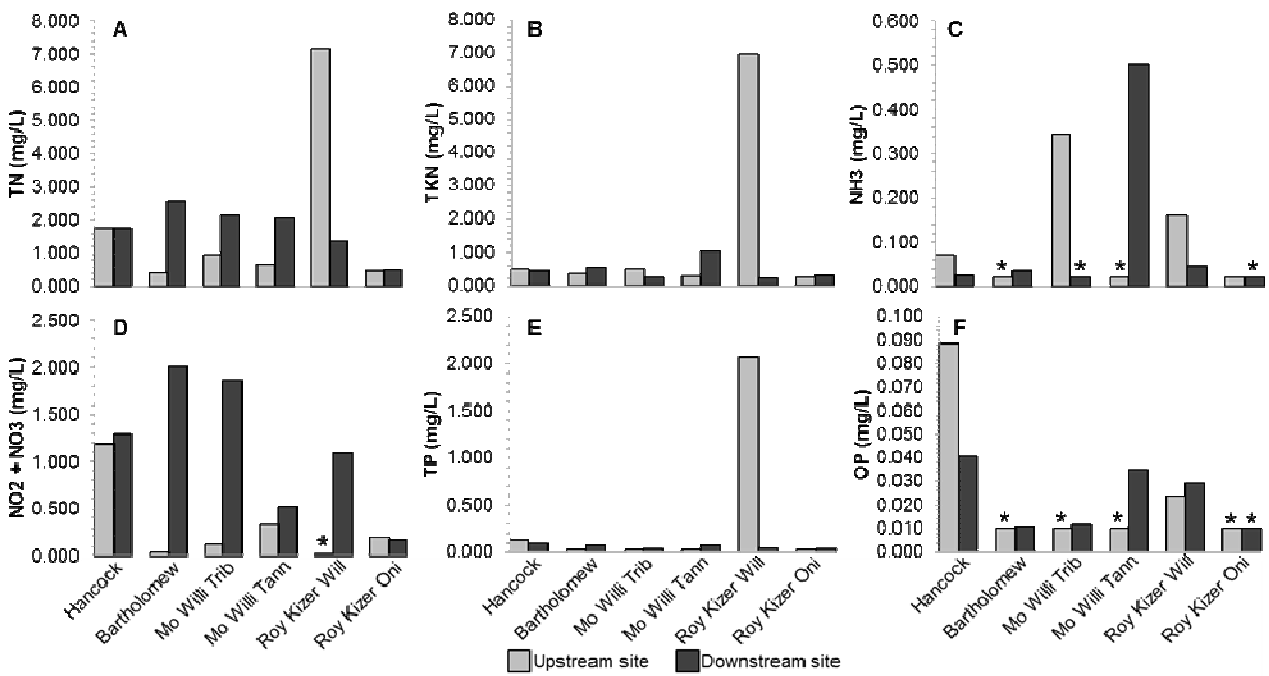

Figure 7. Total nitrogen (A), total kjeldahl nitrogen (B), ammonia (C), nitrate and nitrite (D), total phosphorus (E), and orthophosphate (F) at upstream and downstream sample sites. * indicates sample concentrations were below detection limits.

The total phosphorus concentration at the upstream site on Williamson Creek at the Roy Kizer Golf Course was 2.00 mg/L, two orders of magnitude greater than the background concentrations of about 0.02 mg/L. Although Williamson Creek was dry just upstream of the Roy Kizer Golf Course (site 10776), the creek begins to flow as it winds around the golf course (site 3879). The observed elevated total phosphorus concentration recorded at Williamson Creek above Roy Kizer Kizer Spring may be a result of reclaimed water contribution to the shallow groundwater seepage that creates surface baseflow in this reach.

<u>Benthic Algae</u>

Chlorophyll *a* is commonly used to determine the algal biomass of a system.

Carbon:Nitrogen:Phosphorus stoichiometry in algal cells has been shown to respond to increases in nutrient loads. An increased load of nitrogen or phosphorus leads to lower C:N or C:P ratios in periphyton communities (Hillebrand and Kahlert 2001; Hillebrand and Kahlert 2002; Stelzer and Lamberti 2001; Frost and Elser 2002; Bowman et al. 2005). The increased amounts of nitrogen or phosphorus in the algal cells can lead to an increase in the algal growth rates (Rhee 1973; Droop 1974). This may allow benthic algal biomass to increase more rapidly in nutrient enriched water.

Benthic algae results for the C:P ratios and chlorophyll *a* content of samples collected upstream and downstream of irrigation sites were calculated on a consistent spatial scale (Table 4). Results for the benthic algae samples collected in the tributary to Tannehill Creek downstream of the Morris Williams Golf Course are not shown because a lack of rock substrate in the upstream site did not allow for benthic algae collection and thus there is no data available for comparison.
Table 4: Benthic algae chlorophyll *a* and carbon to phosphorus (C:P) ratios collected upstream and downstream of each reclaim irrigation site.

Site	Benthic Chlorophyll a (mg/m^2)		Benthic C:P Ratio	
	Upstream	Downstream	Upstream	Downstream
Bartholomew	35.40	56.60	11.1	10.4
Morris Williams:Tannehill mainstem	79.40	88.90	15.3	7.8
Hancock: Waller	26.10	65.00	8.0	9.8
Clay/Kizer: Onion	14.10	8.30	17.7	6.1
Clay/Kizer: Williamson	9.20	41.40	26.3	9.8

Benthic chlorophyll *a* (mg/m^2) increased from upstream to downstream at four out of five irrigation sites (Figure 8). Not enough data points exist yet to perform a statistical analysis with strong power to ensure statistical inferences would be accurate; however, the increasing pattern in the benthic chlorophyll *a* suggest an increase in nutrient loading to the creek at the potentially irrigation-influenced downstream sites. In addition, the trophic status as proposed by Dodds et al. (1998) and accepted by the US Environmental Protection Agency (2001) may have shifted from oligotrophic (< 20 mg/m^2 chlorophyll *a*) to mesotrophic (20-70 mg/m^2 chlorophyll *a*) on Williamson Creek upstream to downstream of the Clay/Kizer irrigation area. More sample events are needed at the study reaches before trophic status can be definitively determined.

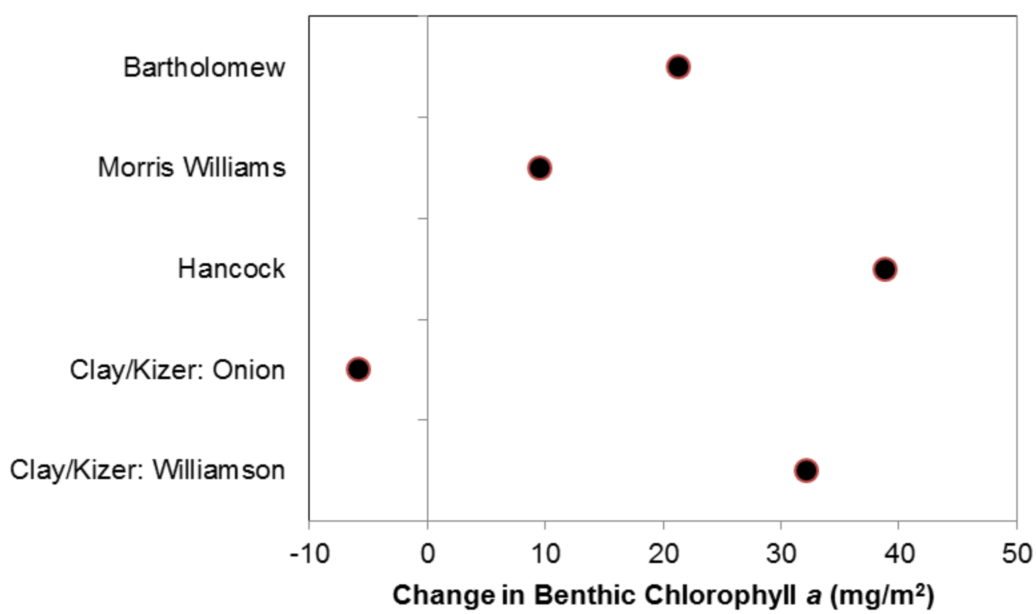

Figure 8: Change in benthic algae chlorophyll *a* (mg/m^2) from upstream to downstream at each site.

Benthic C:P ratios decreased from upstream to downstream at four out of five irrigation sites (Figure 9). Not enough data points exist yet to perform a statistical analysis with strong power to ensure statistical inferences would be accurate; however, the decreasing pattern in the benthic C:P ratios suggest an increase in nutrient load to the creek at the downstream sites.

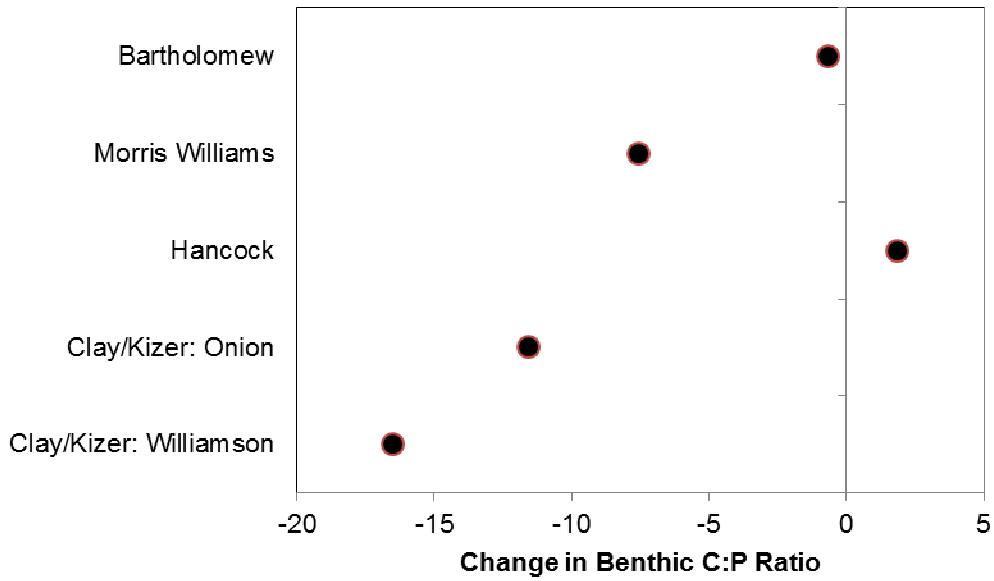

Figure 9: The change in benthic algae carbon to phosphorus (C:P) ratios from upstream to downstream at each reclaim irrigation site.

<u>Nitrogen Isotopes</u>

Lab analysis of the stable nitrogen and oxygen isotope ratios of nitrate collected during the initial October 25, 2014, sampling event revealed that all sites with sufficient nitrate for isotope analysis plotted in the biogenic range, suggesting that the source of nitrogen was manure or wastewater (Figure 10). There was no indication that the nitrogen was originating from precipitation or fertilizer application. Both upstream and downstream sites on Waller plotted in the biogenic range, possibly indicating leaking wastewater infrastructure upstream of the Hancock Golf Course. The inconsistent relationships between the irrigation water sources and the receiving water samples are intriguing, and suggest that differential nitrification and denitrification processes may be occurring.

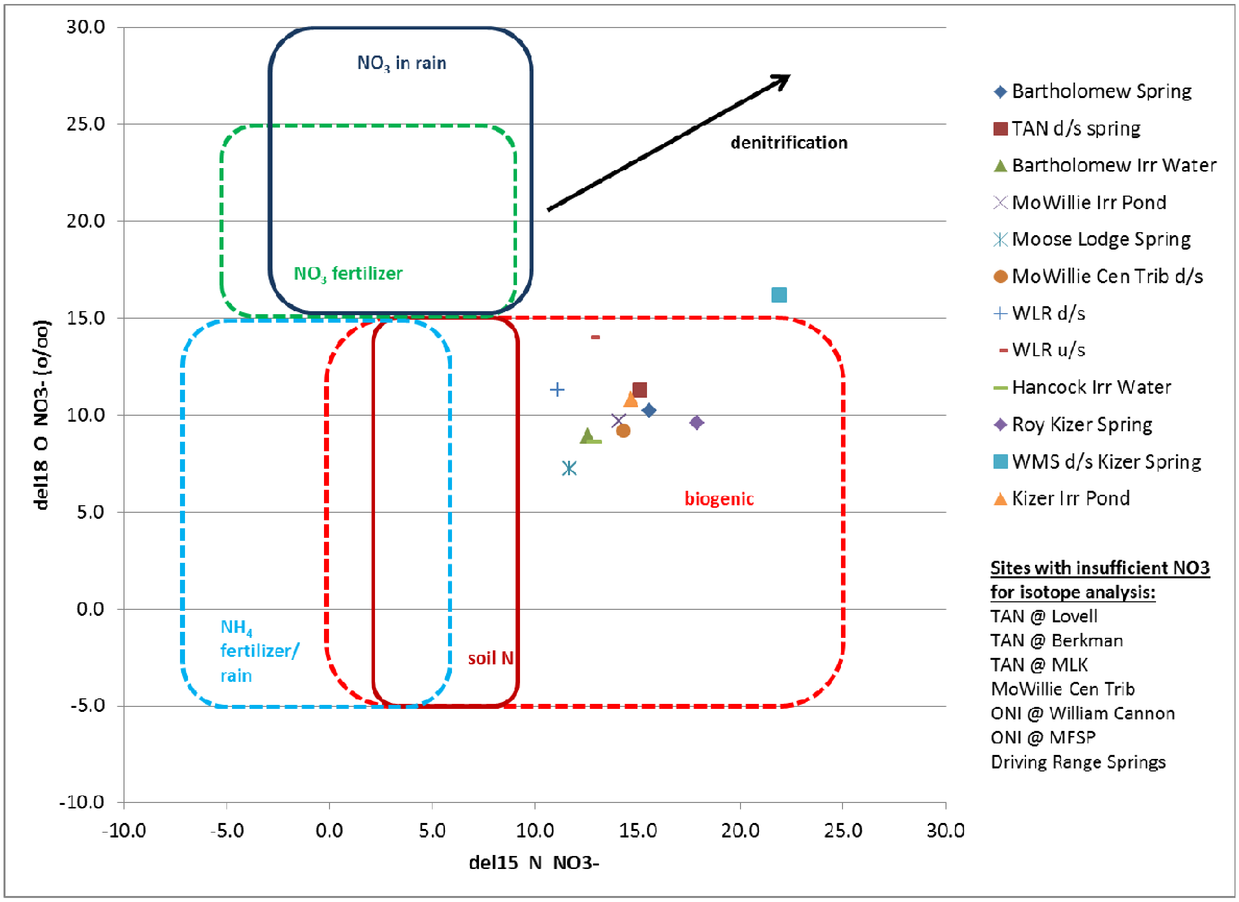

Figure 10. Nitrogen/Oxygen stable isotope ratio plot for study sites.
Source boundaries adapted from Kendall 1998.

Conclusions

As phase one of a two phase study, surface water and groundwater samples were collected on October 15, 2014, at sites upstream and downstream of four locations utilizing City of Austin reclaimed water for irrigation in close proximity to creeks. Samples were analyzed for physiochemical parameters, ions, nutrients, and nitrate isotopes. Benthic algal scrapings were analyzed for area-adjusted algal biomass and nutrient to carbon ratios. Initial analysis of the phase one results indicates:

- Reclaimed water chemical composition changed when the reclaimed water was stored in open holding ponds relative to composition in distribution pipes.
- Conductivity was higher in 4 out of 6 sites downstream of reclaimed water irrigation areas. Average conductivity of upstream surface water sites was 450 μS/cm, and average conductivity of downstream surface water sites was 565 μS/cm.
- Chloride (5/6) and fluoride (4/6) were generally higher in sites downstream of reclaimed water irrigation areas. Average chloride concentrations for upstream surface water sites was 20 mg/L, and average chloride concentrations for downstream surface water sites was 42 mg/L.
- Mass balance of chloride and conductivity, which are conservative in Austin streams, suggests the highest potential influence of reclaimed water on adjacent creeks occurs in Bartholomew Park, the central tributary to Tannehill Branch in Morris Williams Golf Course, and in Williamson Creek adjacent to Jimmy Clay/Roy Kizer Golf Course.
- Ion concentrations generally increase at surface water sites downstream of reclaimed water irrigation.
- Ion composition at springs adjacent to reclaimed water irrigation locations and downstream surface water sites are migrating towards a composition more similar to reclaimed water relative to upstream surface water composition.
- Increased nutrients, especially nitrate plus nitrite, are generally observed in downstream samples. Total nitrogen and total phosphorus were higher in 4 out of 6 sites.
- Nitrogen and oxygen isotopes of nitrate for all sites with sufficient nitrate for analysis indicated that nitrogen was originating from biogenic (manure or wastewater) sources. Nitrogen in Waller Creek upstream of Hancock Golf Course also yielded a biogenic signature.
- Benthic chlorophyll *a* concentrations and C:P ratios suggest an increased loading of nutrients downstream of irrigations sites. Benthic chlorophyll *a* concentrations downstream of the Clay/Kizer Golf Course might be indicative of a change in trophic status of Williamson Creek.

Acknowledgements

This initial sampling event was completed with the assistance of multiple City of Austin Parks and Recreation Department staff, who facilitated access to the park and golf course locations. Additionally, Dan Pedersen with Austin Water provided background information on the use of reclaimed water at these locations, and provided reclaimed water sampling information. Watershed Protection Department expresses thanks to these individuals for assisting with this project.

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Reclaimed water irrigation water quality impact assessment

SR-16-06; April 2016

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City of Austin
Watershed Protection Department

Introduction

In an effort to reduce demand on municipal potable water supply, the City of Austin is increasing utilization of reclaimed water. Although the benefits to potable water supply resources are clearly realized, the reclaimed water contains pollutants which may have the potential to degrade adjacent creeks and springs in some situations. For example, reclaimed water has elevated concentrations of nutrients (such as nitrogen and phosphorus) that may be an order of magnitude higher than stormwater runoff from developed urban land and two orders of magnitude higher relative to ambient surface water condition (Figure 1).

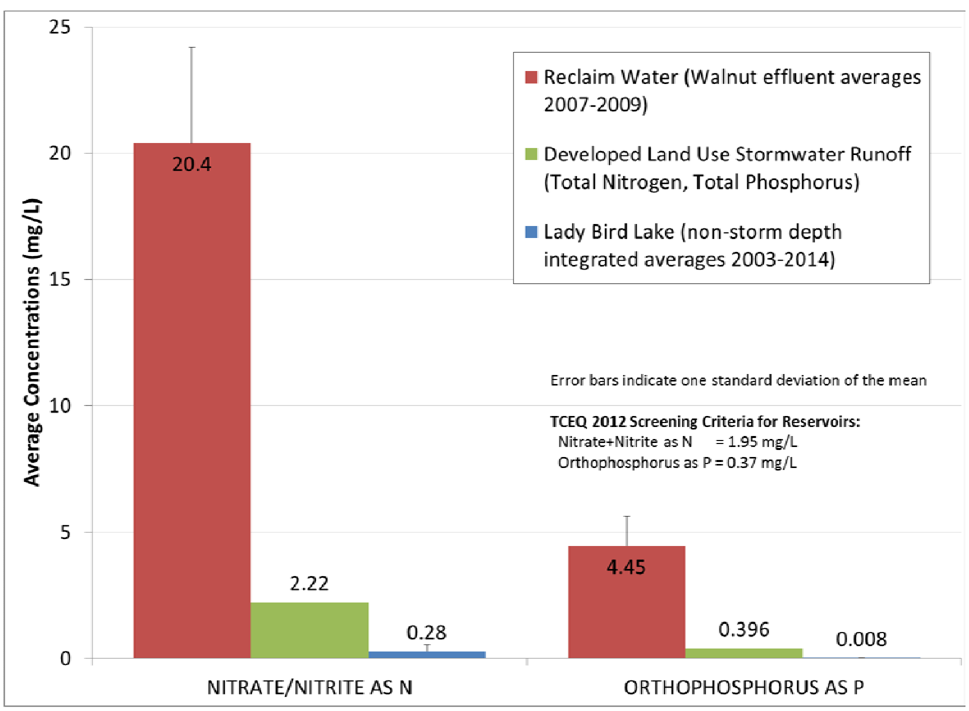

Figure 1: Nutrient concentrations of reclaimed water relative to developed land stormwater runoff and Lady Bird Lake averages (2003-2014). Nutrient concentrations in reclaimed water may be two to three orders of magnitude higher than ambient surface water.

Eutrophication is a well-described process which results when a water body receives an excessive supply of nutrients. In aquatic systems, nutrients such as nitrogen (N) and phosphorus (P) support the growth of algae and aquatic plants. An overabundance of nitrogen and phosphorus can alter the growth habits of algae by increasing to a rate that is faster than the ecosystem can manage. This nutrient enrichment can cause an increase in algal biomass (Figure 2) to the extent that entire reaches of streams show aesthetic degradation (Wharfe et al. 1984, Biggs 1985, Biggs and Price 1987, Welsh et al. 1988), loss of pollution-sensitive invertebrate taxa (Quinn and Hickey 1990), clogging of water intake structures (Biggs 1985), and degradation of dissolved oxygen and pH levels in the water column (Quinn and Gilliland 1989).

Figure 2. Examples of increased algal biomass in which filamentous algae covers the surface water at two sites within the project area; Site 10882 on Tannehill branch near Morris Williams golf course (left) and Site 10778 on Williamson Creek near Roy Kizer golf course (right).

Eutrophication of surface water resulting from land application of treated wastewater has been previously documented in the Austin area. The land application of treated wastewater was identified as a probable source of elevated nitrogen and phosphorus and cause of periphytic algal blooms in upper Bear Creek (Turner 2010). In addition, a strong biogenic nitrogen isotope signature is observed in a spring down-gradient from a golf course utilizing wastewater effluent for irrigation (COA unpublished data) and analysis of stormwater runoff data indicated higher concentrations of nutrients in runoff from golf courses irrigated with wastewater effluent versus golf courses without effluent irrigation (King et al. 2007, COA 2005). U.S. Geological Survey investigations in Florida have previously identified increases in chloride and nitrate in groundwater wells beneath municipal wastewater effluent sprayfields (Pruitt et al. 1988), and land application of treated municipal wastewater effluent was identified as a major source of nitrate to the regional discharge point of the Upper Floridan Aquifer (Katz et al. 2009).

Instream algal biomass can be difficult quantify, and chlorophyll *a* is commonly used as a surrogate to determine the algal biomass of a system. The Texas Commission on Environmental Quality (TCEQ) (2006) showed that benthic (attached) algal chlorophyll *a* could be a better indicator of nutrient enrichment than water-column chlorophyll *a* in small, fast flowing Texas streams. The organic growth of algae, cyanobacteria and heterotrophic microbes attached to the benthic surface is periphyton. The periphyton that colonize the surfaces of submerged rocks and other stable substrate can easily be scraped from the surface with standard methods in order to collect reproducible and standardized samples from streams.

In addition to the chlorophyll *a* concentrations of the periphyton, the carbon to nitrogen to phosphorus (C:N:P) stoichiometry in algal cells has been shown to respond to increases in nutrient loads. An increased load of nitrogen or phosphorus leads to lower carbon to nitrogen or carbon to phosphorus ratios in stream and lake periphyton communities (Hillebrand and Kahlert 2001, Hillebrand and Kahlert 2002, Stelzer and Lamberti 2001, Frost and Elser 2002, Bowman et al. 2005). The increased amounts of nitrogen or phosphorus in the algal cells can lead to an increase in the algal growth rates (Rhee 1973, Droop 1974). This may allow benthic algal biomass to increase more rapidly in nutrient enriched water or contribute to nutrient spiraling downstream by increasing nutrients available to downstream reaches.

In the context of potential stream nutrient enrichment, the concerns related to the application of reclaimed water in close proximity of creeks include:

- migration of the reclaimed water to the creeks and shallow groundwater through infiltration and lateral groundwater flow;
- direct irrigation into creeks during improper spray application; and/or
- excessive constituent loading into riparian soils that exceed natural assimilative capacities and consequent transportation to creeks during runoff events.

To enable evaluation of the potential impacts to surface and groundwater quality, City of Austin Watershed Protection Department staff collected water samples from creeks and springs adjacent to locations with reclaimed water irrigation occurring within the Critical Water Quality Zone (CWQZ) and/or floodplain as defined by the City of Austin Land Development Code. This project was conducted in two phases.

Phase 1 sampling was a one-time sample effort of upstream and downstream conditions relative to on-site reclaimed water and local spring discharge in October of 2014. The results of Phase 1 sampling (Clamann et al. 2015) illuminated spatial and temporal variability and allowed application of robust statistical analysis methods which enabled the determination of the sampling locations and frequencies for Phase 2.

Phase 2 sampling included four sample events during the summer of 2015. The following is a summary of the combined results of the Phase 1 and Phase 2 sampling from on-site reclaimed water, surface water, groundwater and periphyton. The results of the Phase 2 sampling supported many of the preliminary Phase 1 conclusions.

Methods

<u>Field Methods</u>

The field investigation for Phase 1 was conducted on October 15, 2014. Phase 2 field investigations were conducted on July 23, August 27, September 24, and October 20 of 2015. Physiochemical parameters were collected in the field using a Hydrolab multiprobe water quality sonde. Spring and stream discharge was measured with a Marsh-McBirney Flowmate. Water samples from reclaimed water sources (irrigation lines and ponds), surface water (creeks), groundwater (spring discharge) and periphyton (from rock scrapings) were collected by WPD staff, preserved in ice, and delivered to the Lower Colorado River Authority laboratory for analysis following City of Austin standard operating procedures (WRE SOP 2013).

Phase 1 of this study included 21 sites which were located within one park and three golf courses that receive application of reclaimed water (Table 1 and Figure 3). Sites included four known springs (10765, 661, 662, and 10769), on-site reclaimed water irrigation source ponds or supply lines (10767, 10775, 10779, and 10768), and upstream/downstream sample sites on creeks (3858/10767, 10773/625, 3879/10778, 10770/10772, and 843/10771). The Phase 2 of this study included 15 sites within one park and two golf courses (Table 1 and Figure 3). In addition to the samples collected at the sites listed in Table 1, each event included one field replicate sample to document potential for variance within a site.

Table 1: Site list and sample schedule

Location	Site number and name	Purpose	Phase 1	Phase 2			
			Oct 2014	Jul 2015	Aug 2015	Sep 2015	Oct 2015
Bartholomew Park	3858 Tannehill Creek @ Berkman Dr	upstream of irrigation	✓	x	✓	✓	no flow
	10766 Tannehill downstream Bartholomew Spring	downstream of irrigation	✓	x	✓	✓	✓
	10767 Bartholomew Park Irrigation water	source water for irrigation	✓	x	✓	✓	✓
	10765 Bartholomew Spring	groundwater spring	✓				
Hancock Golf Course	10773 Waller Creek @ 45th	upstream of irrigation	✓				
	625 Waller Creek @ 38th	downstream of irrigation	✓				
	10775 Hancock Irrigation Water	source water for irrigation	✓				
Morris Williams Golf Course	843 Tannehill @ Lovell	upstream of irrigation	✓	✓	✓	✓	✓
	10771 Tannehill @ MLK	downstream of irrigation	✓	✓	✓	✓	✓
	10770 Morris Williams Central Trib upstream	upstream of irrigation	✓	✓	✓	✓	✓
	10772 Morris Williams Central Trib downstream	downstream of irrigation	✓	✓	✓	✓	✓
	10768 Morris Williams Irrigation Pond	source water for irrigation	✓	✓	✓	✓	✓
	10769 Moose Lodge Spring	groundwater spring	✓				
	10882 Tannehill 340ft downstream of Lovell	Downstream of seep			✓	✓	✓
Roy Kizer Golf Course	10776 Williamson downstream Pleasant Valley	upstream of irrigation	Dry	✓	Dry	Dry	Dry
	3879 Williamson Creek at Dove Springs Park	upstream of spring	✓	✓	✓	✓	Dry
	661 Roy Kizer Spring	groundwater spring	✓	✓	✓	✓	✓
	10778 Williamson downstream Roy Kizer Spring	downstream of spring	✓	✓	✓	✓	Dry
	10779 Roy Kizer Reclaim Water Pond	source water for irrigation	✓	✓	✓	✓	✓
	10883 Roy Kizer Reclaimed Water Pipe	source water for irrigation		✓	✓	✓	✓
	65 Onion Creek at William Cannon	upstream of irrigation	✓				
	253 Onion Creek at McKinney Falls upper pool	downstream of irrigation	✓				
	662 Driving Range Spring	groundwater spring	✓				

shaded = sample collected, unshaded = sample not collected
"Dry" = site did not have baseflow,
"no flow" = site was sampled for periphyton, but not water chemistry due to lack of baseflow
"x" = site not sampled because facility damage; no irrigation for previous month due to repairs.
blank = site was not part of the QAPP at the time of sampling

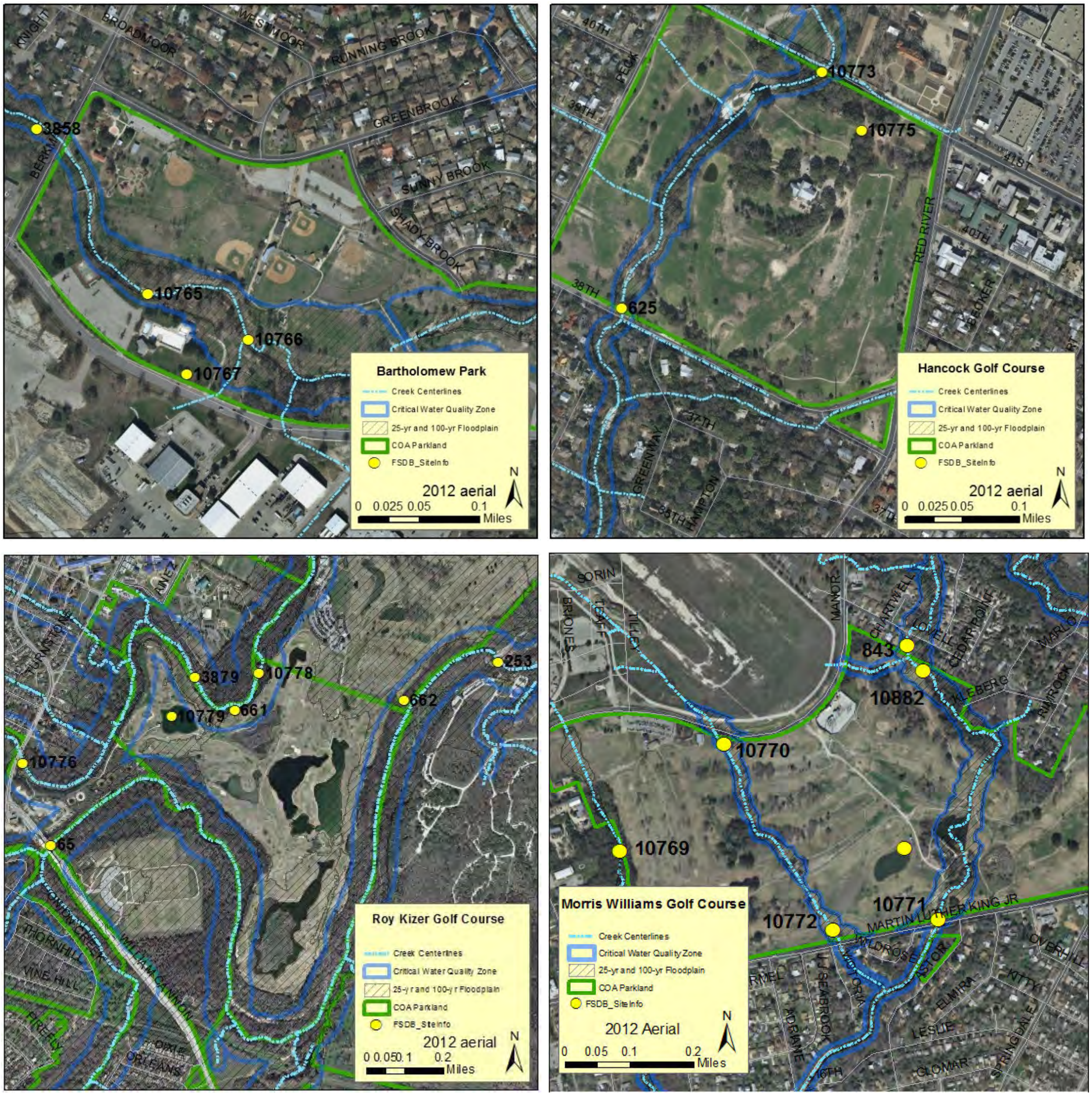

Figure 3: Sample locations at City of Austin parks and golf courses selected to determine potential for impacts to surface and spring water for the Phase 1 and Phase 2 sample events.

Not all sites from Phase 1 were sampled during the Phase 2 field efforts. Sites that were dropped following the Phase 1 sample events include:

- Hancock golf course sites were dropped from the Phase 2 study because the Phase 1 results indicated that the surface water upstream (Waller Creek) of the site was already too highly impacted by pollutant load to provide adequate resolution of contributing impacts within the site.
- Sites on Onion Creek were dropped from Phase 2 due to the large contributing drainage area and resulting high discharge of Onion Creek confounding interpretation of potential impacts.

As shown in Table 1, not all scheduled sites were sampled during all sampling events due to circumstances beyond control, including:

- Bartholomew Park was not sampled in July 2016 because application of reclaimed water was temporarily halted prior to and during the July event due to damages to the irrigation system. Sampling at Bartholomew Park resumed immediately following the repair and subsequent resumption of irrigation system operation.
- Williamson at Pleasant Valley (site 10776) was originally intended to represent upstream conditions for the segment of Williamson Creek at Clay/Kizer golf course. However, it was predominately dry during the sample period. This site was replaced by Williamson at Dove Springs (site 3879) because the stream began producing baseflow near this section of Roy Kizer Golf Course. Accurate total stream discharge was difficult to measure at this location due to a portion of the discharge flowing through the cobble/gravel alluvial substrate. Although Williamson at Dove Springs was used to represent upstream conditions for Williamson Creek, based on its location relative to the golf course it may have already been impacted (and/or creek discharge produced) by the migration of golf course irrigation water.

Water samples were evaluated for conventional field parameters, nutrients, metals, ions and isotopes (Table 2). In addition to these parameters, the periphyton from rocks (epilithon) was collected from rocks randomly selected from within the riffles upstream and downstream of irrigation areas within Bartholomew Park, Roy Kizer, and the mainstem of Tannehill Creek at Morris Williams. As per City of Austin Standard Operating Procedures, rocks were collected from undisturbed areas in the riffle downstream of the water sample and before other sampling had occurred. Relatively flat rocks were selected to ensure a consistent sample area. An area of 19.6 cm^2 was scraped from each rock and placed into a shallow collecting pan (WRE SOP 2013). Each rock was rinsed with deionized water to flush epilithon from the rock. Material from nine rocks in each riffle was composited in the collection pan and then placed into one darkened sample bottle and one regular sample bottle with H_2SO_4 for preservation. Samples were analyzed for Chorophyll *a*, pheophytin, total organic carbon, total phosphorus, ammonia, nitrate+nitrite, and total Kjeldahl nitrogen. Total nitrogen was calculated by taking the sum of nitrate+nitrite and total Kjeldahl nitrogen. Chlorophyll *a*, total organic carbon, total phosphorus, and total nitrogen were then converted to mg/m^2 from mg/L.

Rainfall (inches) for the Williamson and Tannehill watersheds was downloaded from RainVieux and plotted with the monthly volume of reclaimed water irrigated at each site for the project's duration (October 2014 to December 2015). Total nitrogen in the water column, benthic carbon to phosphorus ratios (C:P), benthic carbon to nitrogen ratios (C:N), and benthic chlorophyll *a* were plotted for each sampling event in order to visualize the difference between upstream and downstream concentrations over time.

Table 2: Parameter List

Location	Site number and name	Water Type	Phase 1 Parameters	Phase 2 Parameters
Bartholomew Park	3858 Tannehill Creek @ Berkman Dr	creek	L, F, RS, I	L, F, RS
	10766 Tannehill downstream Bartholomew Spring	creek	L, F, RS, I	L, F, RS
	10767 Bartholomew Park Irrigation water	irrigation	L, F, I	L, F
	10765 Bartholomew Spring	spring	L, F, I	L, F
Hancock Golf Course	10773 Waller Creek @ 45th	creek	L, F, RS, I	
	625 Waller Creek @ 38th	creek	L, F, RS, I	
	10775 Hancock Irrigation Water	irrigation	L, F, I	L, F
Morris Williams Golf Course	843 Tannehill @ Lovell	creek	L, F, RS, I	L, F, RS
	10771 Tannehill @ MLK	creek	L, F, RS, I	L, F, RS
	10770 Morris Williams Central Trib upstream	creek	L, F, I	L, F
	10772 Morris Williams Central Trib downstream	creek	L, F, I	L, F
	10768 Morris Williams Irrigation Pond	irrigation	L, F, I	L, F
	10769 Moose Lodge Spring	spring	L, F, I	L, F
	10882 Tannehill 340ft downstream of Lovell	creek		L, F
Roy Kizer Golf Course	10776 Williamson downstream Pleasant Valley	creek	L, F, RS, I	L, F, RS
	3879 Williamson Creek at Dove Springs Park	creek	L, F, RS, I	L, F, RS
	661 Roy Kizer Spring	spring	L, F, I	L, F
	10778 Williamson downstream Roy Kizer Spring	creek	L, F, RS, I	L, F, RS
	10779 Roy Kizer Reclaim Water Pond	irrigation	L, F, I	L, F
	10883 Roy Kizer Reclaimed Water Pipe	irrigation		L, F
	65 Onion Creek at William Cannon	creek	L, F, RS, I	
	253 Onion Creek at McKinney Falls upper pool	creek	L, F, RS, I	
	662 Driving Range Spring	spring	L, F, I	

**Parameters: L = Lab F=Field RS=Rock Scrapings I=isotopes

Parameters collected during the sampling events included “Field”, “Lab”, “Rock Scraping” and “Isotopes” as described below. Due to the expense, only Phase 1 samples include isotopic evaluation. Springs, reclaimed water source, and sites without appropriate substrate did not include rock scrapings.

FIELD
Conductivity
Dissolved Oxygen
Temperature
pH
Stream Discharge (flow)

ROCK SCRAPINGS
Nitrate+nitrite as N
Ammonia as N
Total Kjeldahl Nitrogen as N
Phosphorus as P
Total Organic Carbon (TOC)
Chlorophyll *a*
Pheophytin

LAB
Metals (Ca, Mg, Na, K, Sr)
Ions (Cl, F, SO_4)
Alkalinity (Calcium Carbonate)
Nitrate+nitrite as N
Ammonia as N
Total Kjeldahl Nitrogen as N
Phosphorus as P
Orthophosphorus as P
Total Organic Carbon (TOC)

ISOTOPES
Nitrogen-15/Nitrogen-14 Ratio
Oxygen-18/Oxygen-16 Ratio

Analysis Methods

Two general methods were used to determine whether reclaimed water has an impact on adjacent water resources: inferential statistical analysis and theory. Inferential statistical analysis looks solely at the data and tests whether any structure in the data is from a disturbance or is merely due to random chance. Theory comes from the application of first principles and describes the mechanism by which the disturbance manifests itself. Thus, theory can not only predict whether an impact can be detected, but can also be used to estimate the magnitude of its impact. Additionally, any data collected can be used to validate the theory. In combination, these two methods can demonstrate a preponderance of evidence with inferential statistics providing a potential relationship among the data and the theory pointing to the likely causation of that relationship.

Inferential Statistical Analysis

To test whether there was an impact to the receiving water from reclaimed water irrigation; paired differences were calculated for each stream segment receiving reclaimed water. That is, for each site visit, concentration results from the downstream samples were subtracted from concentration results from the upstream samples. The average and standard deviation for these paired differences were calculated and then used to compute confidence intervals. This technique is used to improve the precision of the data by eliminating an additional source of variation (i.e. the variation that comes from taking samples at different times of the year).

Given paired differenced confidence intervals at each stream segment, one may compute the probability that the mean paired difference at each stream segment is equal to zero (i.e. not impacted). Thus, paired differences were calculated for each stream segment and for each analyte and ratio of nutrient concentrations (Gelman and Hill 2007).

Theory

A conceptual model can be used to express how a potential mechanism (e.g. irrigating reclaimed water) might impact an adjacent receiving stream. A plausible conceptual model might invoke mixing upstream water with a distributed loading of this irrigated water along the length of the creek to yield the downstream water composition. This model is graphically represented in Figure 4.

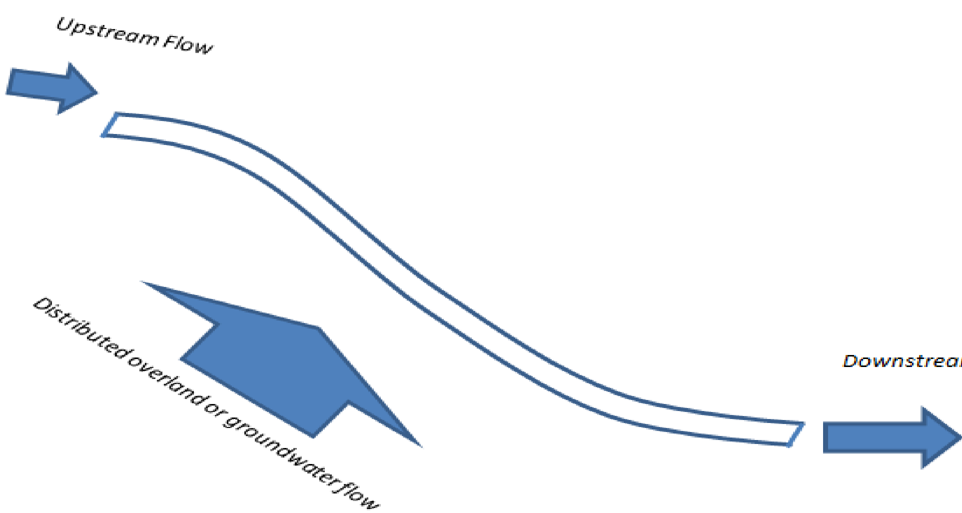

Figure 4: Schematic of reclaimed water irrigation conceptual model.

Applying Conservation of Mass, the mass entering a system must equal the mass exiting the system, assuming no storage within a stream segment. Thus, this model can be represented by:

$$\textit{Upstream mass flow rate} + \textit{Distributed mass flow rate} = \textit{Downstream mass flow rate} \quad (1)$$

or:

$$Q_{up} \cdot C_{up} + Q_{ReWW} \cdot C_{ReWW} = (Q_{up} + Q_{ReWW}) \cdot C_{down} \quad (2)$$

where Q_{up} = upstream flowrate (ft^3/s);
Q_{ReWW} = reclaimed water flowrate (ft^3/s);
C_{up} = upstream concentration (mg/L);
C_{ReWW} = reclaimed water concentration (mg/L); and
C_{down} = downstream concentration (mg/L).

Rearranging to solve for C_{down}:

$$C_{down} = F \cdot C_{up} + (1 - F) \cdot C_{ReWW} \quad (3)$$

where

$$F = \frac{Q_{Up}}{(Q_{up} + Q_{ReWW})} \quad \text{and} \quad 1 - F = \frac{Q_{ReWW}}{(Q_{up} + Q_{ReWW})}$$

From this, one can see that the downstream concentration is a flow-weighted mixture of upstream and reclaimed water concentrations. If there is no impact, then C_{down} would equal C_{up}, and F would equal unity. Unfortunately, determining F from field measurements of flow may prove difficult over the course of a season due to fluctuations in the flow. Furthermore, estimating the amount of Q_{ReWW} that contributes to the stream requires considerable assumptions on irrigation application rate. Additionally, there may be other influences on the stream, such as groundwater. For example, if there was an additional source to the stream (such as from groundwater) the conceptual model would not change too drastically. There would be an F_1 for the upstream contribution, an F_2 for the groundwater contribution, and a $(1\text{-}F_1\text{-}F_2)$ for the reclaimed water. However, Equation 3 represents a simple and first iteration of a model, and it will be shown that this simplistic model may be a fair representation of the creek systems in the parks and golf courses.

To arrive at a practical (and long term) estimate of the impact from reclaimed water, it helps to look at the concentrations of the sampled downstream water relative to the upstream and reclaimed water concentrations. Equation 3 establishes that the downstream concentration is, in effect, a mixture experiment. That is, it is postulated that the downstream concentration is a mixture of upstream and reclaimed water concentration. Thus, data collected on the downstream concentration can be used to quantify the extent of this mixture. However, a suite of analytes, rather than a single constituent, is sampled in the surface water. Determining how this suite interacts with each other and their environment is difficult. To overcome this complexity, the geochemical computer program, pHREEQc (pH-REdox-EQulibrium) was used to simulate the chemical mixing of the upstream waters with reclaimed water under equilibrium conditions. The interaction of reclaimed water with the soil (itself a mixture of calcite and montmorillonite) was also simulated in an attempt to more accurately mimic the physical processes of the reclaimed water.

Using this approach, the model predicted downstream concentrations for each of the nine surface water analytes, given the upstream and reclaimed water data at each park. The goal was to determine which fraction, F, corresponded to the downstream surface water concentrations for all nine surface water analytes. Then, that fraction was compared to actual flow measurements, Q_{up} and $Q_{up}+Q_{ReWW}$, to validate the model. An additional validation using Piper plots is used to show the influence of downstream samples to either upstream samples or reclaimed water samples. The pHREEQc model, however, does not quantify the amount of nutrient (or chemical ion) uptake of algal biomass in the creek. However, the amount of chlorophyll *a* and any nutrient ratios can serve as an indication to the presence of this uptake and to the implication of an impact on the stream.

The conceptual model provides a framework with which to examine all of the data. One can postulate four different hypotheses using this overlying framework that can be tested using the data:

- <u>Hypothesis 1</u> is that there is no impact on the stream. That is, the reclaimed water has been effectively absorbed into the soil without migrating to the stream. Under this scenario, inferences from the paired difference analyses of the surface water concentrations and the benthic ratios show no impact, and F is equal to, or approximately 1 (i.e. $F \simeq 1$).
- <u>Hypothesis 2</u> is that there is an impact and can be seen in one of two potential data sets, the surface water data or the benthic ratio data. Thus, Hypothesis 2 is actually made up of two sub-hypotheses.
  - <u>Hypothesis 2a</u> is that there is an impact, but it is only on the surface water. Therefore, the nutrients have yet to be converted to algal biomass due to insufficient light conditions. Inferences from the paired difference analyses would not reveal an impact in the benthic ratios. Rather, the paired difference analyses would show an impact in the surface water and F is less than 1(i.e. $F < 1$).
  - <u>Hypothesis 2b</u> is that there is an impact, but it is only on the benthic substrate. Under this supposition, the reclaimed water irrigation is impacting the surface water, but algae are converting the composition of the water to benthic form. $F < 1$, but this can only be inferred from the paired differences in the nutrient ratios and cannot be inferred from the pHREEQc model.
- <u>Hypothesis 3</u> is that an additional source is interfering with any impacts of the reclaimed water on the surface water; thus, confounding any inferences from the paired differences. Also, the flow ratio, *F*, would not be consistent among the nine surface water analytes. In this case, samples from this additional source would need to be obtained and the conceptual model (and pHREEQc model) would require a re-specification. A failure of the data sets to inform on the plausibility of either Hypotheses 1 or 2 may point to this Hypothesis.

The data from the cumulative sample periods of Phase 1 and Phase 2 are assessed under this framework to determine the presence or absence of an impact.

Results and Discussion

A cursory review of the data indicates that most downstream sites are higher in nitrogen than upstream sites, indicating that the creeks may be experiencing an impact from the application of high nutrient reclaimed water irrigation. However, it is important to thoroughly explore the data to ensure that the differences are statistically significant and can be attributed to the potential source.

The Methods section of this report describes an analytical model that provides three exclusive hypotheses to explore the data and explain the phenomena (i.e. characterize the change in the composition of downstream surface water). This section presents the empirical data and describes how it informs the possibility of one of the three competing hypotheses. The results of the sampling are evaluated in the context of four primary data sets. These sets are presented in the following order to substantiate the presence of an impact in the surface water, the percent contribution of the impact in the surface water, and characterize the impact in the surface water as follows:

1. <u>**Confidence Intervals**</u> of the mean paired differences in the surface water are depicted as bar graphs to serve as a preliminary indication of whether or not there is an impact to each of the creeks (Figures 5-12) and can be seen in tabular form in Appendix A. Additionally, confidence intervals of the mean benthic ratios of C:N, C:P and chlorophyll *a* (Figures 13-15) are presented

as further evidence of a potential impact as benthic communities uptake nutrients from the water column and may indicate impacts which might otherwise be hidden in the water column.

2. The **<u>Geochemical pHREEQc model</u>** estimates the percent contribution that the downstream water is influenced by the upstream water (Figures 16-19).

3. **<u>Piper plots</u>** are graphical depictions that distinguish different types of source waters and can be used to identify changes, trends, and mixing of ion compositions (Figures 21- 23).

4. **<u>Total nitrogen along with benthic stoichiometry differences</u>** are depicted in order to visualize differences in chemical and biological water quality from the potential impact (Figures 30-33).

The four data sets described above can be linked to the four hypotheses in the following manner:

- **Hypothesis 1** would be disproven if any of the confidence intervals (either surface water or benthic ratios) show a significant difference from upstream to downstream. That is, if the confidence intervals for the mean paired difference in the surface water or periphyton do not encompass zero, then that is an indication of an impact on the surface water.

- The Geochemical pHREEQc model can be used to examine the plausibility of **Hypothesis 2a and 2b**. The model provides an estimate of the percent contribution of upstream water and reclaimed water to the downstream water. If this percent contribution is consistent among a majority of the constituents sampled then that not only points to the source of the disturbance in the creek, but also to the amount of influence in the creek from reclaimed water. Further strength is given to this hypothesis if the analysis of confidence intervals also shows a non-zero confidence interval for each constituent in the creek. Flow measurements and piper plots can be used to validate this hypothesis.

- Finally, if the analysis provides insignificant results without a clear signal, then that may suggest **Hypothesis 3** (i.e. an alternative source of the impact) which would require more studies to determine the alternative source.

<u>Confidence Intervals of the Mean Paired Differences</u>
Confidence intervals of the mean paired difference in surface water parameters for each creek are presented in Figures 5 through 12. Bartholomew Park is shown first (Figures 5 and 6), followed by Morris Williams at the mainstem (Figures 7 and 8), Morris Williams at the central tributary (Figures 9 and 10), and finally Roy Kizer at Williamson Creek (Figures 11 and 12). The tabular results from this analysis can be found in Appendix A. Nitrate+nitrite is significantly higher in the downstream surface water sample (Figure 5) while there is a significant increase in the magnesium, potassium, sulfate, alkalinity, chloride, sodium, and calcium ions in the downstream surface water (Figure 6) at Bartholomew Park. The positive differences in these analytes imply surface water impacts from the reclaimed water irrigation at Bartholomew Park.

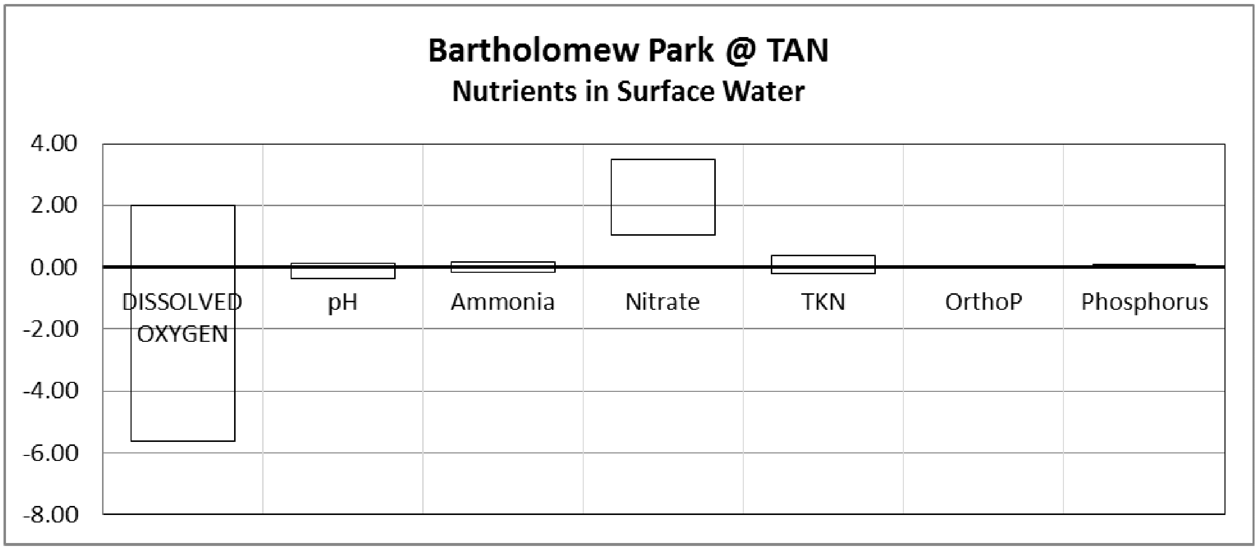

Figure 5: Confidence Intervals of the Mean Paired Difference of dissolved oxygen, pH, and nutrients in the water column collected upstream and downstream of Bartholomew Park. Nitrate was significantly higher in Tannehill Creek downstream of Bartholomew Park.

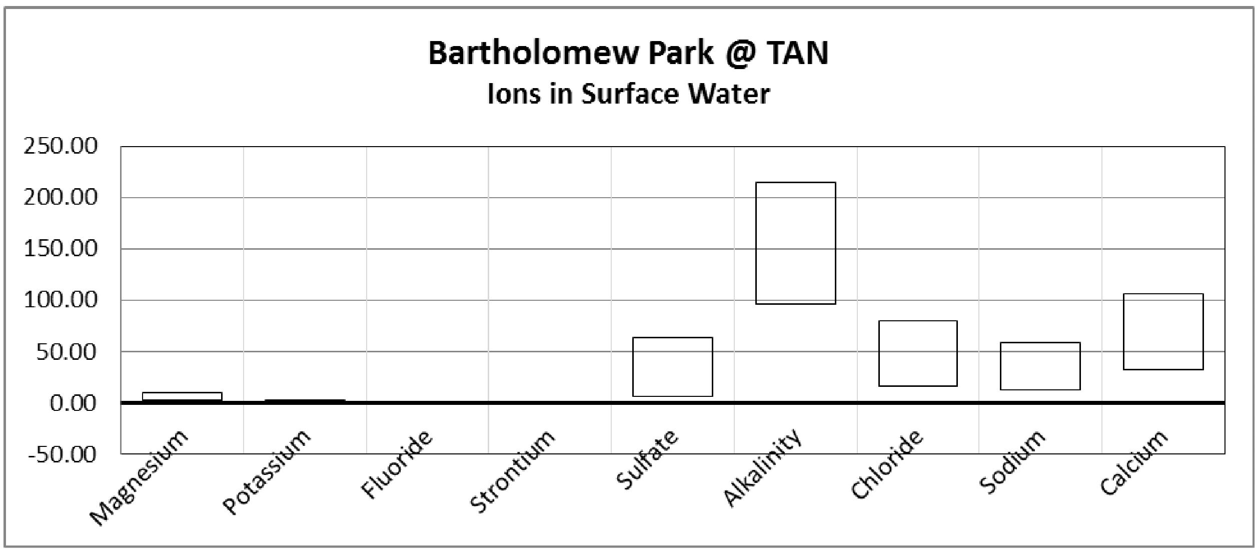

Figure 6: Confidence Intervals of the Mean Paired Difference of ions in the water column collected upstream and downstream of Bartholomew Park. Magnesium, potassium, sulfate, alkalinity, chloride, sodium, and calcium were all significantly higher in Tannehill Creek downstream of Bartholomew Park.

Figures 7 and 8 indicate that there is statistically no difference for most of the nutrients and ions in the surface water at Morris Williams in the mainstem of Tannehill Creek with three exceptions. Alkalinity and calcium ions are at concentrations *less* than upstream samples. TKN is at concentrations slightly higher than upstream. Thus, this particular analysis does not indicate a discernable impact from reclaimed water[1]. However, under the framework stated in the Methods section, there remains the possibility that any impact has been latent in the benthic algae data (Hypothesis 3) or is being diluted by

[1] Given the number of comparisons made in this report, a small but non trivial number of those comparisons may be expected to give a Type I error. It is possible, but cannot be verified with current data, that TKN is a false positive.

groundwater influence (Hypothesis 4). The most likely hypothesis for this creek will be determined from results for the pHREEQc model in the next section.

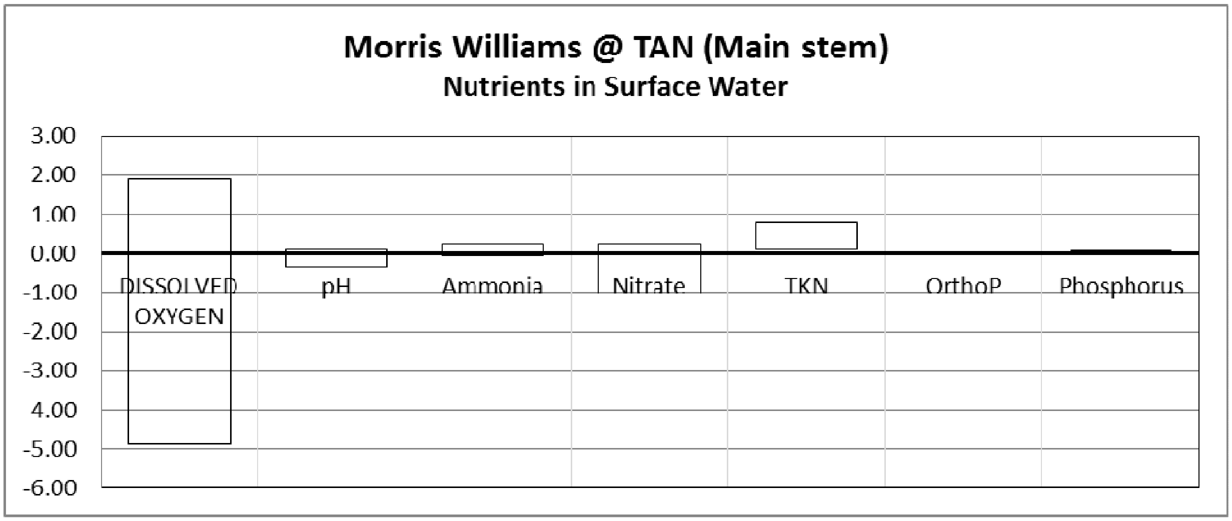

Figure 7: Confidence Intervals of the Mean Paired Difference of DO, pH, and nutrients in the water column collected upstream and downstream of Morris Williams. Of these parameters, only TKN was significantly higher in Tannehill Creek downstream of Morris Williams.

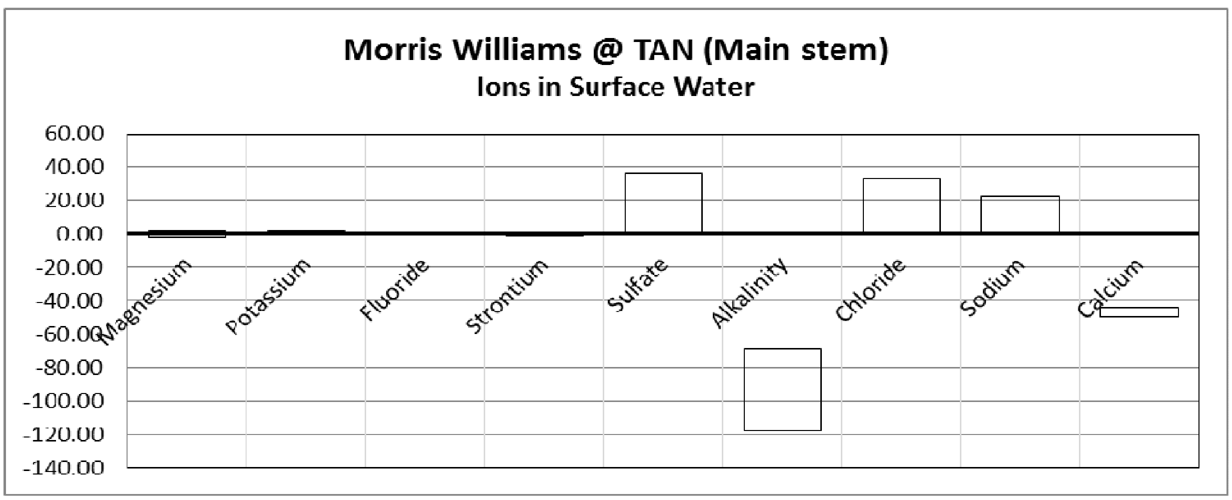

Figure 8: Confidence Intervals of the Mean Paired Difference of ions in the water column collected upstream and downstream of Morris Williams. Alkalinity and calcium were significantly lower in Tannehill Creek downstream of Morris Williams.

Similarly to Morris Williams mainstem of Tannehill Creek, Figures 9 and 10 below show that for the Morris Williams central tributary, differences between downstream and upstream samples were insignificant, with the exception of pH and nitrate.

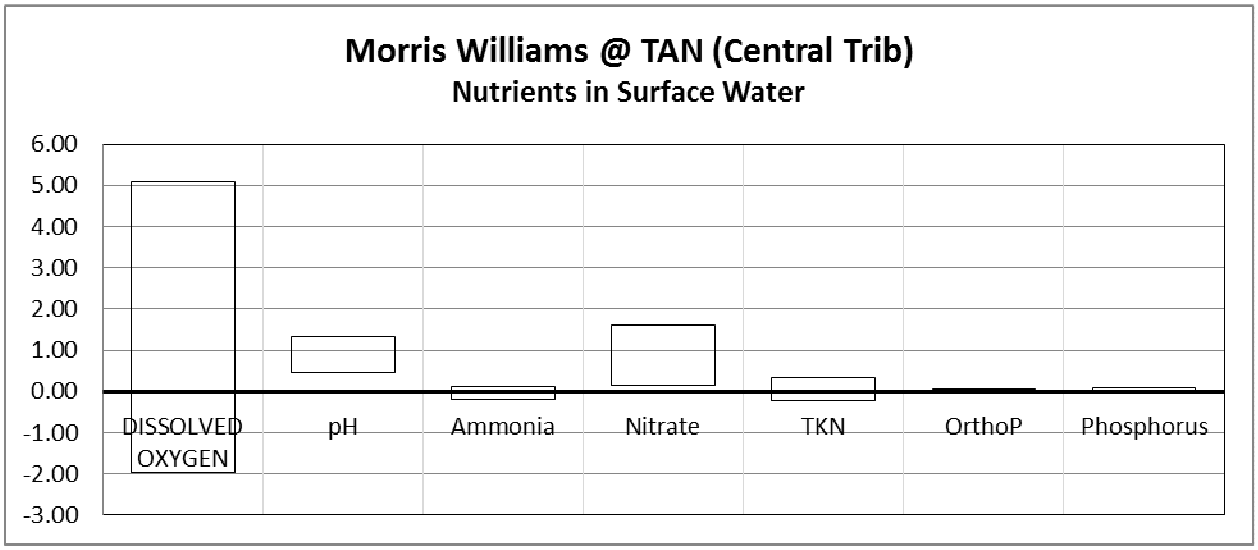

Figure 9: Confidence Intervals of the Mean Paired Difference of dissolved oxygen, pH, and nutrients in the water column collected upstream and downstream of Morris Williams within a tributary running through the golf course. Out of these parameters, only pH and nitrate were significantly higher in the tributary downstream of Morris Williams.

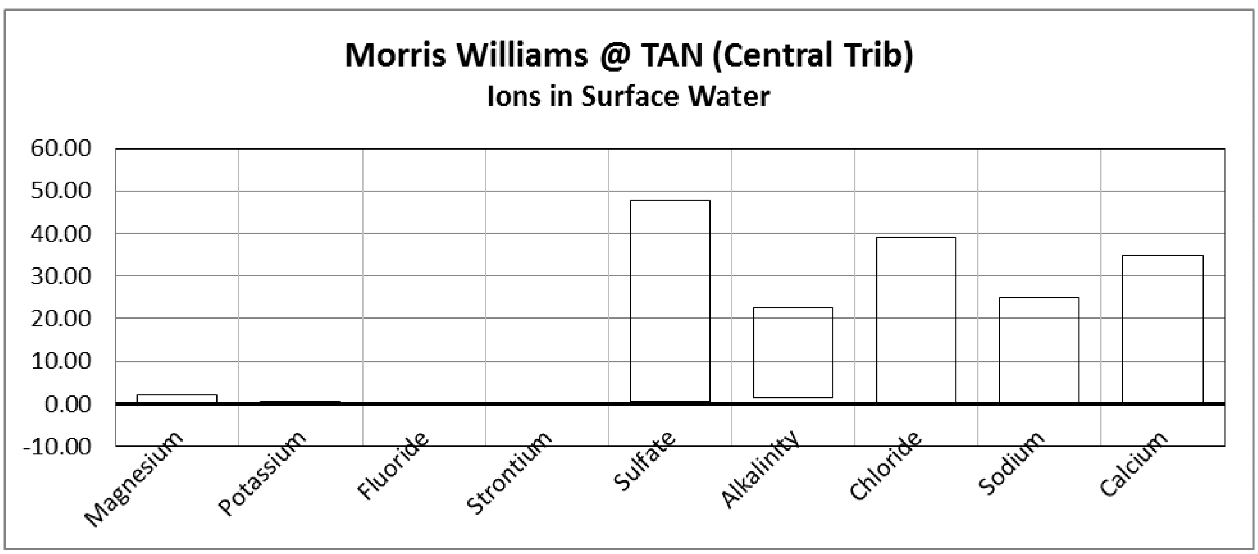

Figure 10: Confidence Intervals of the Mean Paired Difference of ions in the water column collected upstream and downstream of Morris Williams within a tributary running through the golf course. None of these parameter were significantly different in the tributary downstream of Morris Williams.

Results from Roy Kizer on Williamson Creek (Figures 11 and 12) showed impacts similar to that of Bartholomew Park. Nitrate+nitrite concentrations in downstream samples were higher than upstream samples and most of the downstream samples showed elevated ion concentrations compared to upstream indicating that there was a statistically significant impact to the surface water

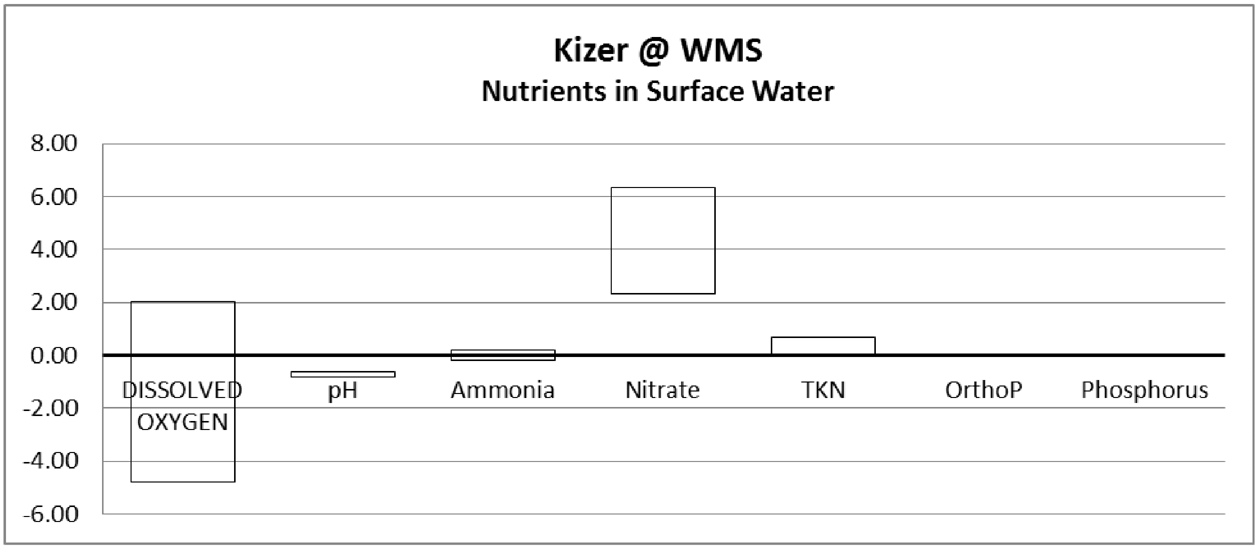

Figure 11: Confidence Intervals of the Mean Paired Difference of dissolved oxygen, pH, and nutrients in the water column collected upstream and downstream of Roy Kizer. Nitrate was significantly higher in Williamson Creek downstream of Roy Kizer while the pH was significantly lower.

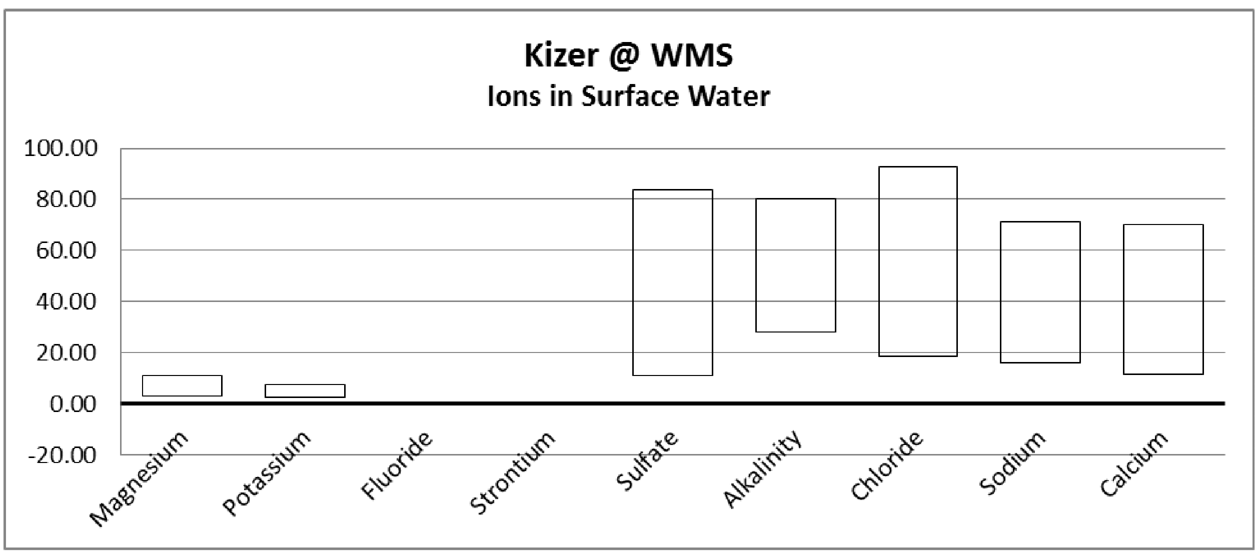

Figure 12: Confidence Intervals of the Mean Paired Difference of ions in the water column collected upstream and downstream of Roy Kizer. Magnesium, potassium, sulfate, alkalinity, chloride, sodium, and calcium were significantly higher in Williamson Creek downstream of Roy Kizer.

Based on the confidence intervals of the mean paired difference in surface water parameters for each creek, there appears to be statistically significant differences in samples taken between upstream and downstream locations at Bartholomew Park and at Roy Kizer. Differences in surface water samples taken between upstream and downstream samples at the two tributaries in Morris Williams were more ambiguous. However, the next set of confidence intervals to be discussed (regarding the benthic ratios) reduces that ambiguity.

None of the creeks sampled showed any differences in fluoride or strontium concentrations. It is suspected that fluoride, which is a negatively charged ion, is only attenuated by vegetation, since cation ion exchange with clay in soil is unlikely due to the negative charge of clay. Plant uptake studies using fluoride-rich irrigation water show that fluoride accumulates in various plant parts. The root accumulates most of the fluoride supplied through irrigation water (Pollick 2004).

<u>Confidence Intervals of the C:P, C:N and benthic chlorophyll *a*</u>

Results for the benthic C:P, benthic C:N, and benthic chlorophyll *a* content of samples collected upstream and downstream of irrigation sites are displayed in Appendix C with additional graphs in Appendix D. Benthic C:P significantly decreased from upstream to downstream as demonstrated by a mean paired difference confidence interval that did not include zero (Table 3). There was no significant difference from upstream to downstream for benthic C:N or benthic chlorophyll *a* as the individual confidence intervals each contained zero.

Table 3: Mean paired difference (95% confidence interval) in the benthic C:P, benthic C:N, and benthic chlorophyll *a* content computed downstream to upstream. The probability that the difference is strictly positive or negative is also included. A decrease in the benthic ratios or increase in the chlorophyll *a* content would show degradation downstream.

Parameter	Mean Difference	95% CI	Prob > 0	Prob < 0
Carbon to Phosphorus	-6.48	(-10.49,-2.76)	--	1.0
Carbon to Nitrogen	-0.71	(-1.96,0.38)	--	0.89
Chlorophyll *a*	16.72	(-23.26,53.58)	0.821	--

The decreasing pattern in the benthic C:P (Figure 13A) suggests an increase in phosphorus load to the creek which was not detectable in the water column, possibly due to nutrient uptake by the benthic algae. This is most pronounced in samples collected in the mainstem of Tannehill creek upstream and downstream of the Morris Williams golf course (Figure 13B).

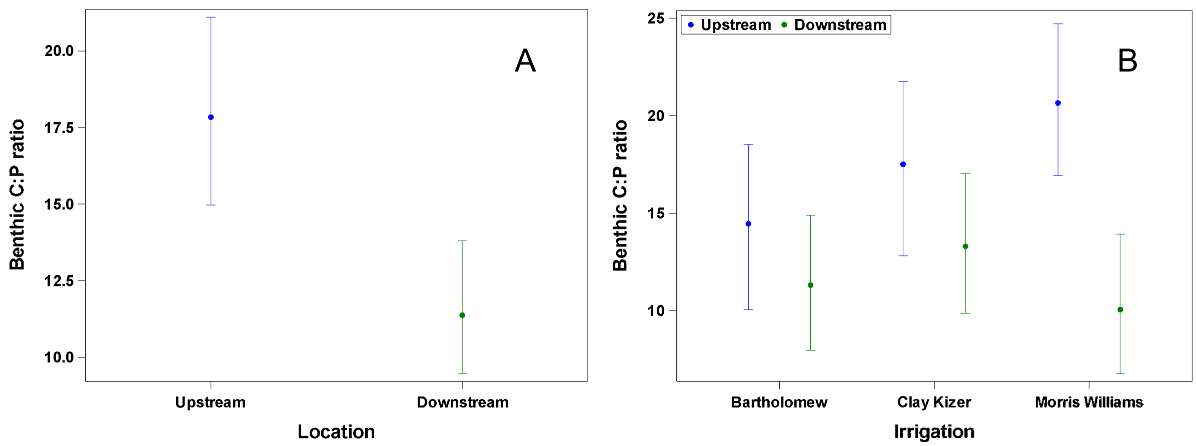

Figure 13: The mean and 95% Confidence Interval of benthic Carbon (C) to Phosphorus (P) in upstream and downstream samples pooled from all reclaim irrigation sites (A), and partially pooled for distinction between each reclaimed irrigation site (B). The benthic C:P was significantly lower downstream of reclaimed irrigation sites.

There was no significant pairwise difference in benthic C:N upstream and downstream of the reclaimed water irrigation sites. There was a decreasing pattern in the benthic C:N (Figure 14A) which would indicate degradation downstream of the irrigations sites and the probability of the difference to be below zero was 0.89 based on the data collected. This suggests that the decreasing pattern might be real and not a random phenomenon. Given several more sampling events, the pairwise difference in C:N upstream and downstream of the irrigations sites might be determined to be significant.

The variability for benthic C:N in all upstream site locations was much higher than the variability at downstream locations (Figure 14B). This was most likely due to a high benthic C:N collected upstream of Clay Kizer in October 2014. This would impact the variability at all upstream sites because the data is partially pooled and not analyzed separately.

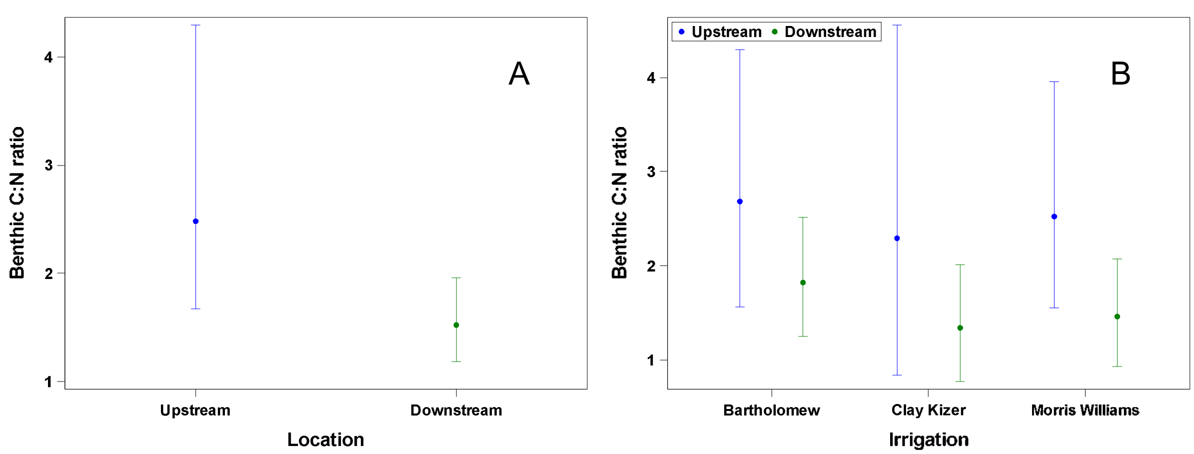

Figure 14: The mean and 95% Confidence Interval of benthic C:N in upstream and downstream samples pooled from all reclaimed irrigation sites (A), and partially pooled for distinction between each reclaimed irrigation site (B). There was no significant pairwise difference in benthic C:N upstream to downstream.

There was not a significant difference in benthic chlorophyll *a* (mg/m^2) upstream to downstream of the reclaimed water irrigation sites. While it appeared that there were higher chlorophyll *a* concentrations downstream of irrigation sites when all of the data was pooled (Figure 15A), the parameter was highly variable and no clear pattern was discernible based on pairwise comparisons. The probability for chlorophyll *a* concentrations to be higher downstream of the irrigation sites was only 0.821 and it is unclear what inference further sampling would lead to without the inclusion of more explanatory variables. Chlorophyll *a* concentrations at Bartholomew showed more signs of degradation than did the other two irrigation sites (Figure 15B). The Bartholomew Park irrigation site may be impacting Tannehill Creek upstream of the Morris Williams golf course irrigation site.

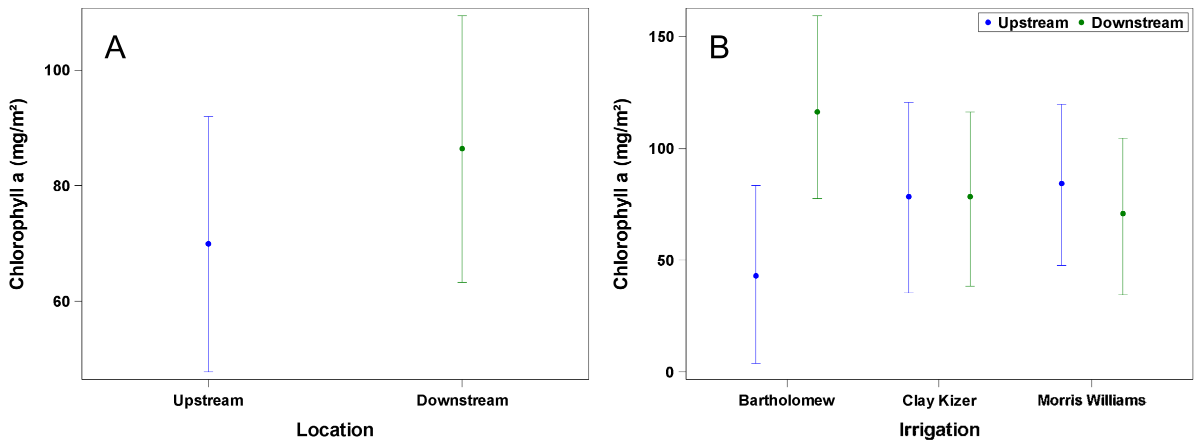

Figure 15: The mean and 95% Confidence Interval of benthic algae chlorophyll *a* (mg/m^2) in upstream and downstream samples pooled from all reclaimed irrigation sites (A), and partially pooled for distinction between each reclaimed irrigation site (B). There was no significant pairwise difference in benthic chlorophyll *a* upstream to downstream.

Geochemical pHREEQc Model

Analysis of the confidence intervals on Bartholomew Park and Roy Kizer infers an impact to surface water from reclaimed water irrigation. If this is true, it should be supported by pHREEQc modeling. The overarching framework postulated in the Methods section suggests that any contribution to the downstream samples originate from a flow-weighted mixture of two sources: upstream water and reclaimed water. This section examines the influence of these two samples on the downstream sample. Medians of the upstream and reclaimed water concentration samples were input into the model (see Appendix B for the values). Table 4 shows an estimate of the downstream concentration under either solely upstream influenced conditions or under solely reclaimed water influenced conditions for the nine key ions collected in the surface water.

Table 4: Estimated downstream concentrations (mg/L) from the pHREEQc model under solely upstream influenced conditions and solely reclaimed water influenced conditions.

	Cl^-	Na^+	Mg^{+2}	K^+	SO_4^{-2}	F^-	NO_3^-	Alk	Ca^{+2}
Bartholomew Park @ TAN									
Upstream	15.5	12.5	3.6	2.3	13.9	0.3	0.1	108	44.4
ReclaimedWW	113.6	120.2	25.1	14.4	134.6	1.9	29.1	382	161.6
Morris Williams @ TAN (mainstem)									
Upstream	34.0	25.4	5.4	1.9	30.2	0.3	0.7	243	102.0
ReclaimedWW	113.0	120.7	25.4	14.4	134.6	1.9	29.1	382	161.1
Morris Williams @ TAN (central tributary)									
Upstream	16	19.7	4.6	2.6	10.8	0.4	0.3	210	72.2
ReclaimedWW	113.0	120.7	25.2	14.4	134.6	1.9	29.1	382	158.4
Roy Kizer @ WMS									
Upstream	31.0	20.0	7.3	2.2	33.2	0.28	0.7	200	83.2
ReclaimedWW	132.1	84.2	14.5	5.4	125.9	0.43	9.0	282	187.7

If the conceptual model is close to reality, then the concentrations of the downstream samples should be between the upstream and reclaimed water concentrations bounds, inclusively, given in Table 4 for each ion for each park. Downstream samples with concentrations close to those of upstream samples would be mostly upstream influenced, whereas downstream samples with concentrations close to those of the model-predicted reclaimed water samples would be mostly influenced by reclaimed water.

Applying the conceptual model also gives the advantage that the fractional amount of influence, *F*, from each source can be inferred. The results from the model can be superimposed on the confidence intervals of the mean concentration for each constituent under upstream, downstream, and reclaimed water samples in Bartholomew Park (Figure 16).

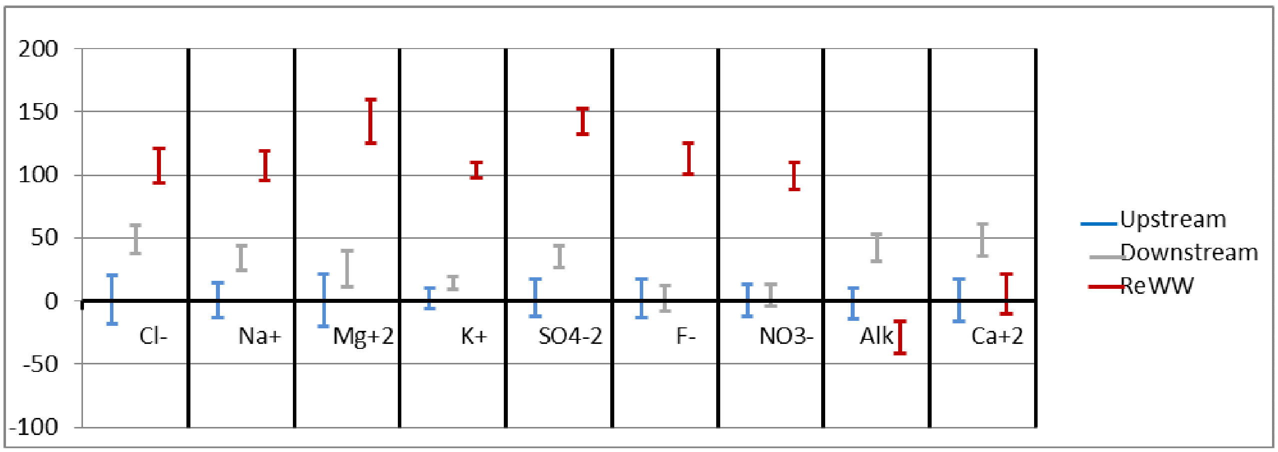

Figure 16: Bartholomew Park pHREEQc Results. The blue, grey, and red bars represent the 99% confidence intervals of the mean concentration for each analyte. Confidence intervals are standardized to a scale of 0 to 100 where 0 denotes the pHREEQc model prediction of the upstream concentration and 100 signifies the pHREEQc model prediction of the reclaimed water after its interaction with the soil. With the exception of fluoride and nitrite, the confidence intervals of the nine downstream constituents (grey bars) encompass approximately a score of 40 on the y-axis. This indicates a 40% contribution from reclaimed water.

As an example to aid interpretation, the pHREEQc model for Bartholomew Park predicted that if only upstream waters were influencing the downstream waters, the downstream samples would have a chloride concentration of 15.5 mg/L (see Table 4) or a standardized score of 0 (i.e. 0% reclaimed water) (see Figure 16). If reclaimed water was the only influence on the downstream sample, then the downstream samples would have a chloride concentration of 113.6 mg/L or a standardized score of 100 (i.e. 100% reclaimed water). The confidence intervals on the mean concentrations for the upstream and reclaimed water samples include (as it should) the 0 and 100 scores, respectively. The confidence intervals of the mean concentrations of the downstream samples, however, all cluster around the score of approximately 40. Thus, one may infer that the downstream waters are composed of 40% reclaimed water and 60% upstream water, which is consistent with paired difference results. Furthermore, flow measurements taken during the sample visits indicate that *F*, the fraction of upstream to downstream flow, averages at about 60%. This is consistent with the pHREEQc results and verifies an impact to the stream at Bartholomew Park (Figure 16).

The Bartholomew Park pHREEQc model predicted alkalinity and calcium concentrations of 382 mg/L and 162 mg/L, respectively, for a purely reclaimed water downstream sample, when the actual reclaimed water sample had concentrations of 28 mg/L and 50 mg/L, respectively. This may indicate that as the reclaimed water is moving through the soil, it is dissolving the calcium in soil and transporting this calcium with it. This may explain why the alkalinity and calcium concentrations in the downstream samples are much higher than that of the upstream or reclaimed water concentrations. Similarly, the pHREEQc model predicted that magnesium concentrations in purely reclaimed water downstream sample would be much lower than that of the actual reclaimed water concentration. This indicates that as the reclaimed water is moving through the soil, it is losing magnesium.

Fluoride and nitrate+nitrite concentrations in the downstream sample do not appear to adhere to the pattern predicted for other constituents at Bartholomew Park. One explanation may be the limited nature of the pHREEQc modeling attempted for this report. Nitrate+nitrite will undergo a conversion to another species that was not input into the model. For fluoride, it is hypothesized that the soil will adsorb the fluoride to make fluorite using a reaction not yet programmed into pHREEQc.

With Bartholomew Park results presented in detail as a case study, modeling results for the remaining creeks can be discussed briefly. The impact from the reclaimed water on the surface water of Morris Williams is either subdued owing to large variability in the samples or non-existent (Figure 17-18). The confidence intervals also show that the surface water in the main stem is losing alkalinity and calcium as it advances downstream. Alkalinity and calcium in the central tributary, on the other hand, are highly variable with both downstream and upstream samples showing similar concentrations. Flow measurements indicate that estimates of *F*, the fraction of upstream to downstream flow, is about 90%, which may explain the lack of an impact on surface water on the main stem. Thus, nutrient ratios for this park may be needed to ascertain an impact.

For the central tributary, however, flow upstream is greater than downstream for two of the four site visits removing the possibility of verifying the actual flow measurements with the pHREEQc results. This variation of flow in time also emphasizes that flow is a confounding factor in the analysis for this creek. Since pHREEQc gave consistent results of *F*, groundwater influences may be ruled out.

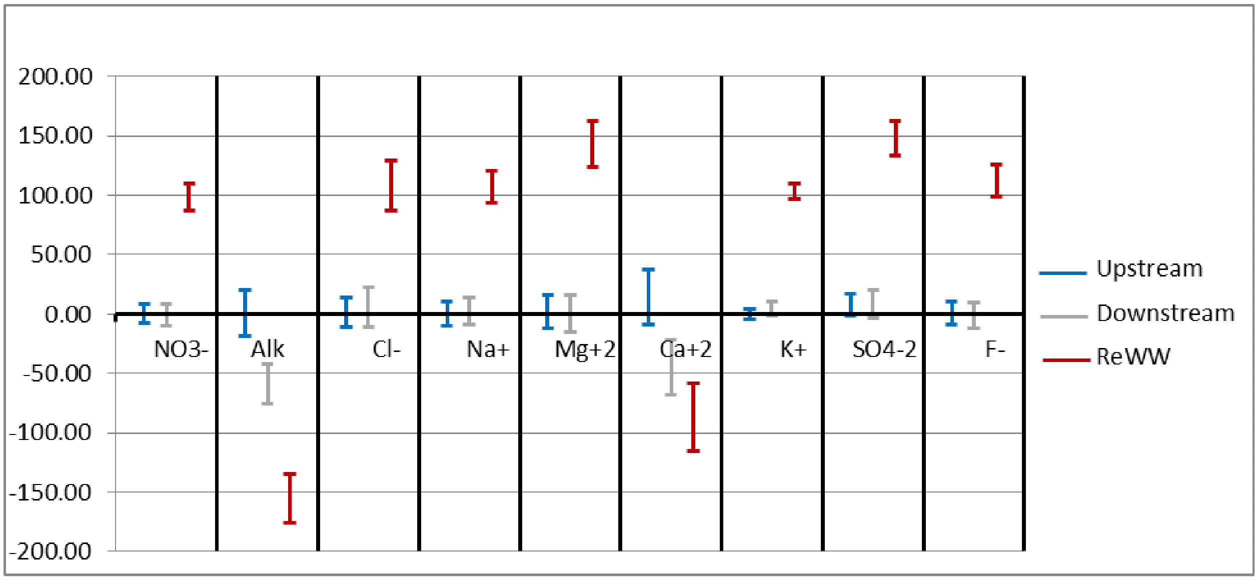

Figure 17: Morris Williams (main stem) pHREEQc Results. The blue, grey, and red bars represent the 99% confidence intervals of the mean concentration for each analyte. Confidence intervals are standardized to a scale of 0 to 100 where 0 denotes the pHREEQc model prediction of the upstream concentration and 100 signifies the pHREEQc model prediction of the reclaimed water after its interaction with the soil. With the exception of alkalinity and calcium, the nine downstream constituents (grey bars) contain a score around zero. This indicates a negligible to small impact on the downstream concentrations from reclaimed water. Benthic ratios are needed to determine the presence of an impact.

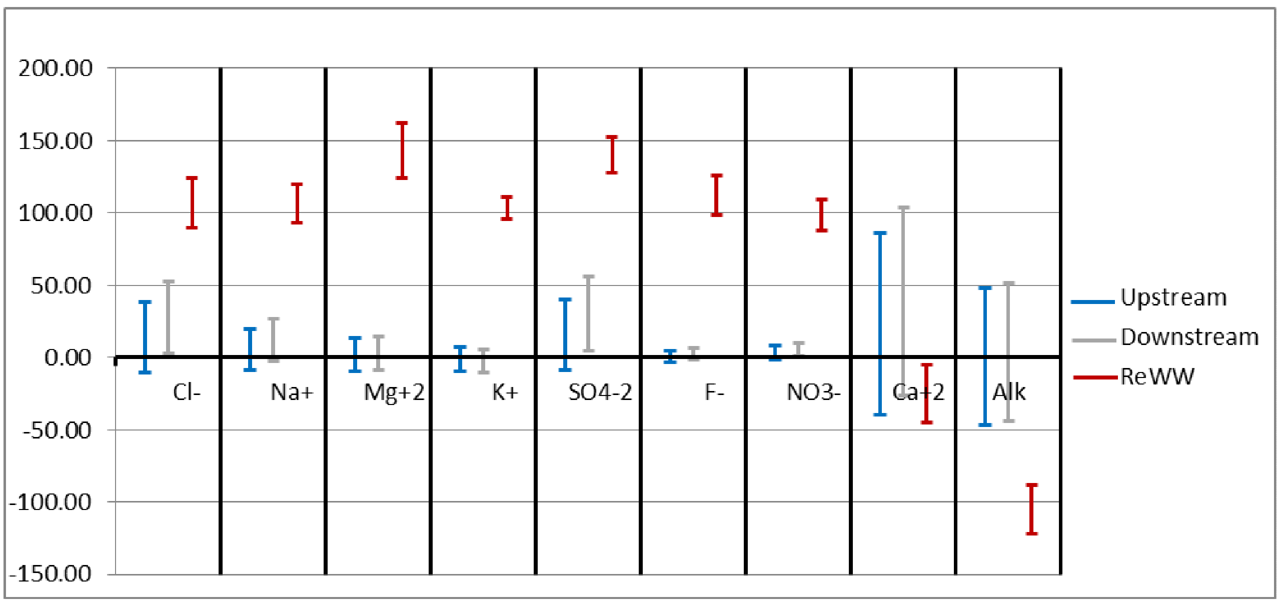

Figure 18: Morris Williams (central tributary) pHREEQc Results. The blue, grey, and red bars represent the 99% confidence intervals of the mean concentration for each analyte. Confidence intervals are standardized to a scale of 0 to 100 where 0 denotes the pHREEQc model prediction of the upstream concentration and 100 signifies the pHREEQc model prediction of the reclaimed water after its interaction with the soil. The downstream constituents (grey bars) have considerable variability making any assessment of impact on the creek difficult. Benthic ratios are needed to determine the presence of an impact.

The impact of the reclaimed water on surface water at the Roy Kizer golf course was similarly assessed (Figure 19). Potassium shows the clearest indication of an influence from reclaimed water at around 30%. This estimate of 30% is certainly within the bounds for chloride, sodium, and magnesium; however, the variability for these analytes dominates any inference that can be made from it. Again, the flow measurements are not consistent across the sampling visits. This makes verification of the pHREEQc model unfeasible. This variation in flow may be contributing to the variability at the site. There exists some variation in the *F* inferred from pHREEQc (Figure 19), which is pointing to a groundwater influence. But given that the paired differences showed an impact in the surface water, this groundwater influence may be considered small relative to the influence of reclaimed water.

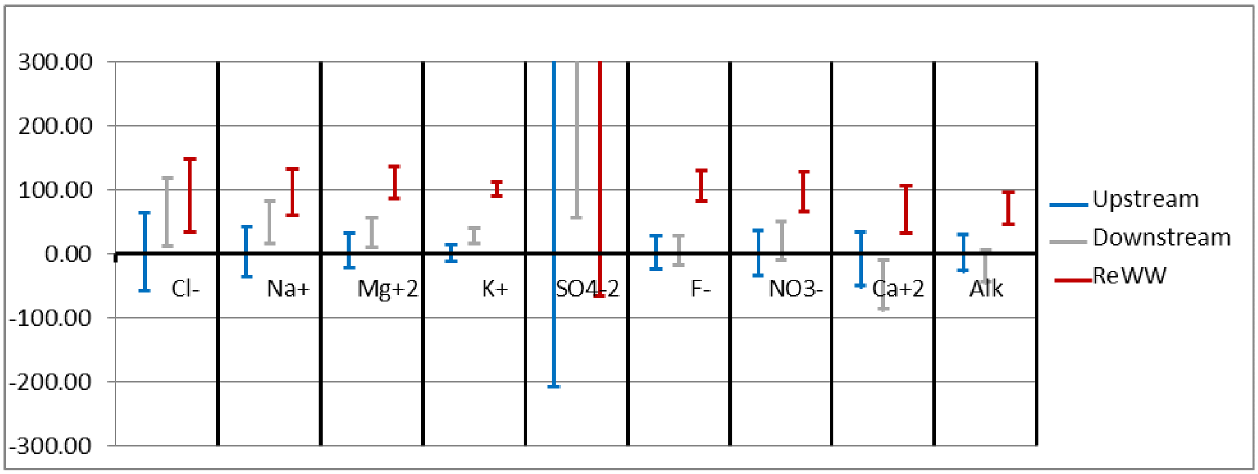

Figure 19: Roy Kizer pHREEQc Results. The blue, grey, and red bars represent the 99% confidence intervals of the mean concentration for each analyte. Confidence intervals are standardized to a scale of 0 to 100 where 0 denotes the pHREEQc model prediction of the upstream concentration and 100 signifies the pHREEQc model prediction of the reclaimed water after its interaction with the soil. The downstream constituents (grey bars) show about a 30% impact due to reclaimed water for chloride, sodium, magnesium, and potassium. The variability in sulfate is extensive and precludes an inference, while downstream concentrations of fluoride and nitrite characteristically show no influence. Downstream concentrations of calcium and alkalinity also appear to show little to no influence due to reclaimed water

<u>Piper Plots</u>

Piper plots, or triangle plots, are typically used to determine the hydrogeochemical facies or classification of natural water. In natural water, the ion composition is controlled by local lithology, the duration of the water-rock and the water-soil interactions, and natural attenuation. In the Austin area, groundwater and surface water is classified as a calcium-bicarbonate hydrogeochemical facies due the carbonate geology that dominates most of the area.

Natural, native groundwater with calcium-bicarbonate hydrogeochemical facies will plot on the left hand side of the diamond-shape area of a piper plot. In contrast, reclaimed water from Austin's municipal supply is considerably higher in sulfate and chloride, and will consequently plot on the right hand side of the diamond-shaped area (Figure 20). The mixing of two distinctly different water types will result in a shift in the ion composition at an impacted monitoring site. In a piper plot, mixing would be indicated if downstream points plot in-between the natural waters on the left and reclaimed water on the right. The magnitude and direction of the linear shift of creek water facies toward the reclaimed water facies would indicate the degree of mixing with or influence from the reclaimed water. Larger shifts will indicate greater amounts of reclaimed water mixing with the natural groundwater or surface water. The magnitude of the shift is also influenced by antecedent weather conditions, creek flow, and irrigation rates. For example, the shift can be muted during high rainfall periods because irrigation rates generally decrease and rainwater runoff has lower concentration of ions.

The mean ion concentrations for calcium, magnesium, potassium, sodium, bicarbonate, chloride, and sulfate at the upstream, the downstream, and the reclaim water monitoring sites are characterized with a piper plot (Figure 20). Each point shown in the diamond-shape and triangular areas is a graphical representation of all ion concentrations reported as the overall percentage of the total cation and anion concentrations.

Consistent with the preliminary results of Phase 1 of this study (Clamann et al. 2014), there is a clear shift in the ion concentrations of downstream samples from a more natural condition towards the more sulfate and chloride-rich composition of reclaimed water (Figure 20). This indicates that reclaimed water is likely mixing with the surface water. The ion composition varies between reclaimed water sources. The reclaimed water irrigated at Bartholomew Park and at Morris Williams Golf Course has a higher sulfate, chloride, and magnesium concentration then the reclaimed water irrigated at Roy Kizer. A similar variation in magnesium concentrations at the springs located on the golf courses that were irrigated with reclaimed water is also reported in a 2007 study (Hiers and Herrington 2007). The variation may be attributed to differences in the chemical composition of the wastewater stream that the two treatment plants (the Walnut Creek Wastewater Treatment Plant and the South Austin Regional Plant) are processing and distributing to the reclaimed water system.

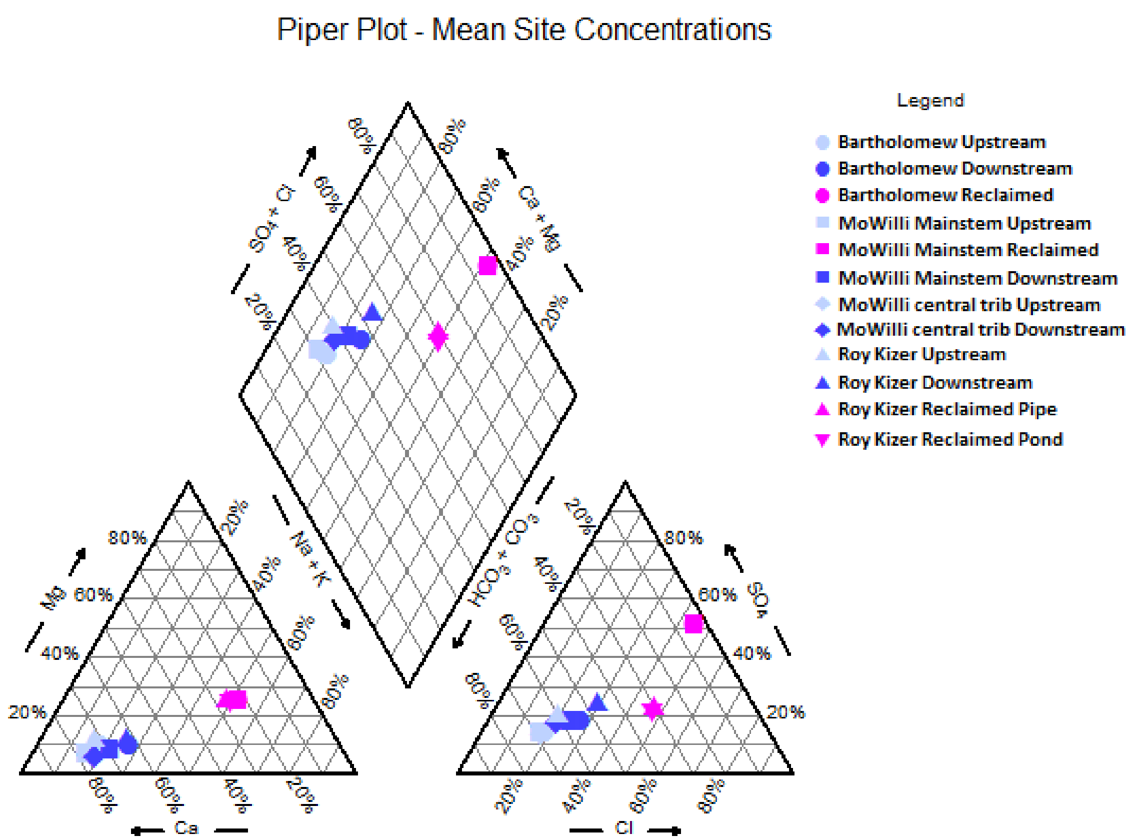

Figure 20: The mean ion concentrations for calcium, magnesium, potassium, sodium, bicarbonate, chloride and sulfate at the upstream, the downstream and the reclaim water monitoring sites.
Upstream sites are in light blue. Downstream sites are in dark blue. Reclaimed Water sites are in purple

Piper plots, of the pHREEQc model ion data for the upstream, the downstream, and the reclaimed water sites was constructed (Figure 21). The plots generally show the same drift in the ion data indicative of reclaimed water mixing with natural water at the downstream monitoring sites, with the exception of the

Morris Williams mainstem monitoring site. The Morris Williams mainstem site simulated ion data is different in that the ion data shows little to no variability and no significant difference in ion composition at the downstream site. This suggests that the upstream site may already be impacted by reclaimed water irrigation activities further upstream at Bartholomew Park and/or Mueller Development, which are located upstream of the Morris William Golf Course. However, it is also plausible that irrigation rates in this portion of the golf course were lower so that natural attenuation from the interaction with the soil and vegetation is sufficient to mute measureable effects in the downstream water chemistry.

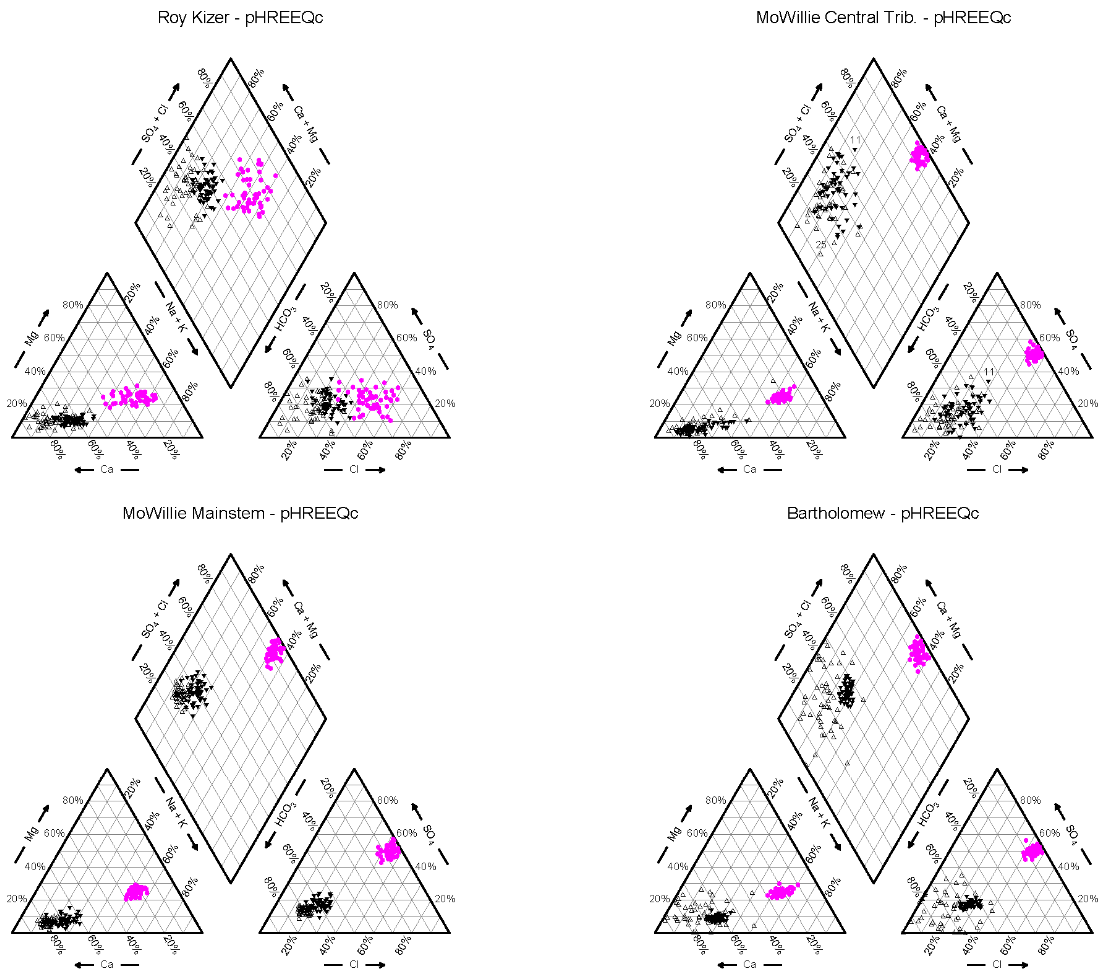

Figure 21: Piper plot of the pHREEQc model ion data for the upstream, the downstream, and the reclaimed source water at each of the study stream reaches

△ = Upstream sites ▲ = Downstream sites ● = Reclaim Water sites

<u>Temporal Trends at Roy Kizer Spring</u>

The Williamson Creek Wastewater Treatment Plant was closed and decommissioned in the early 1970's. Construction of the Roy Kizer Golf Course started in 1994 on the site of the old plant. Around this time the City of Austin discovered that the springs and seeps along Williamson and Onion creeks adjacent to the old treatment plant site had very high nitrate and ammonia concentrations. The δ^{15} Nitrogen isotope samples collected in August 1993 had ratios of 11.6 and 12.9, indicating a biogenic source. Using nitrogen isotope analysis, the nitrogen source was traced to sediment and sludge from the abandoned treatment plant sludge pits. To remediate this impact, during the construction of the golf course the sludge material was stocked piled and saved for use as top dressing for the greens, tee boxes, and fairway areas so that the turf grass could utilize the nutrients within the sludge. The remediation effort was apparently successful in reducing the elevated nitrate levels observed at several springs along Williamson and Onion creeks, including Roy Kizer Spring (Figure 22). A time-series plot of nitrate+nitrite concentrations at Roy Kizer Spring from 1996 to present indicates a sharp drop in nitrate+nitrite concentration during the first four years after construction of the golf course. This reduction in nutrients were presumably due to the remediation efforts as the newly installed turf grass consumed the nitrogen from nutrient-rich sediment and sludge mixture used as top dressing. By 1998, the nutrient concentrations in spring discharge had decreased to less than 5 mg/L of nitrate+nitrite as nitrogen.

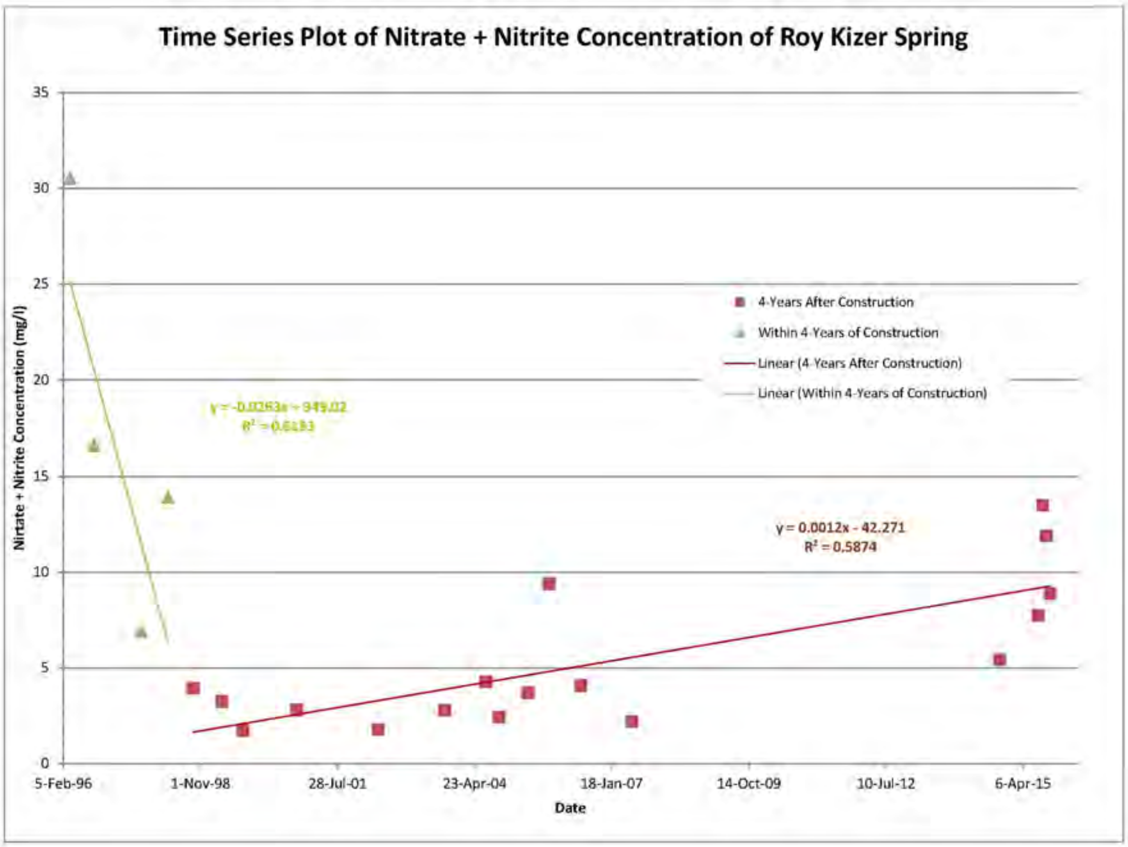

Figure 22: Time-series plot of nitrate+nitrite concentration at Roy Kizer Spring

Based on nitrate levels collected since 1998 and most recently in 2014 and 2015 associated with this study, it appears that nitrate+nitrite concentrations have recently increased to between 5 mg/L and 15 mg/L (Figure 22). Nitrogen concentrations in this range are unusually high for Austin area groundwater which typically has concentrations around 2 mg/L. Of the 2,693 nitrate+ nitrite observations collected by the City of Austin from Austin-area springs from 1968 to present, the 10 highest values were collected from springs on the Jimmy Clay and the Roy Kizer golf courses. Of interest to this study, the 10th highest nitrate+ nitrite value was collected during the recent field efforts on August 27, 2015, at Roy Kizer Spring. Since the Roy Kizer Springshed is located entirely within the golf course, the source of the biogenic influence may be the application of reclaimed water irrigation.

In addition to the spatial differences observed in the ion data between upstream and downstream sites, increases over time in sulfate and chloride concentrations may be observed at Roy Kizer Spring. The spring has occasionally been monitored by the City of Austin since the mid-1990's. Sixteen samples have been collected since August of 1996 to present (Figure 23). Piper plots indicate that the groundwater discharge from the spring is enriched with sulfate and chloride likely from reclaimed irrigation water similar to that as shown in the previously described spatial comparison between upstream and downstream sites and the pHREEQc modeled results. Since the springshed for this spring is located entirely within Roy Kizer Golf course, the source for the increase is most likely reclaimed water irrigation and grass management practices.

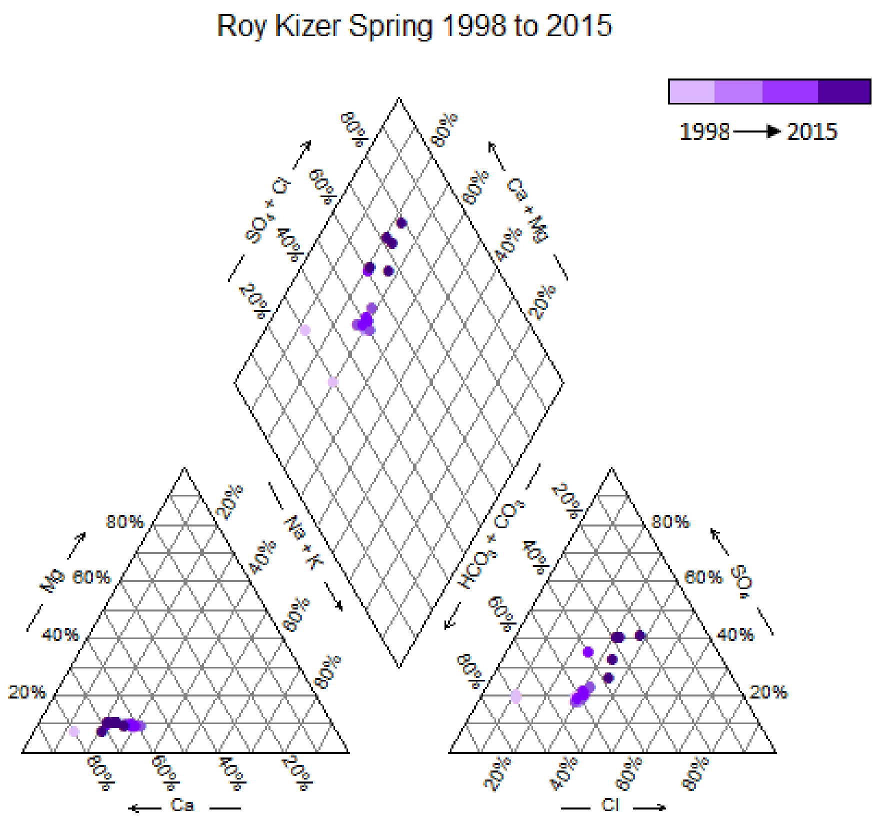

Figure 23: Piper plot of ion data collect at Roy Kizer Spring from August 1998 to December 2015. Note the temporal trend in the middle and right-hand plots that indicate a shift in the composition.

<u>Bivariate plots of specific conductance and nitrate+nitrite nitrogen</u>

Since 1992, the City of Austin Watershed Protection Department has been periodically monitoring selected springs adjacent to several golf courses. At least 25 springs from nine different golf courses have been monitored over the past 25 years. The golf courses include Jimmy Clay, Roy Kizer, Morris Williams, Austin Country Club, Balcones Country Club, Barton Creek Fazio, Barton Creek Crenshaw, Lost Creek and Avery Ranch. Except for Avery Ranch, which uses native surface water from Brushy Creek for irrigation, all of the golf courses use reclaimed water or a mixture of groundwater and reclaimed water for irrigation. The golf course at Great Hills uses both reclaimed water and brackish groundwater from the Trinity Aquifer.

Samples collected at Avery Ranch Spring were used as the background samples for the purposes of this assessment. The mean conductivity at Avery Ranch Spring was 770 µS/cm (95% CI = 741.0-798.3 µS/cm) (Figure 24). The mean conductivity was significantly higher at Roy Kizer Spring (mean =

1120.8 µS/cm, 95% CI = 1016.8-1224.7 µS/cm) (t-test with unequal variance, $p < 0.0001$), which is slightly inside the range of conductance of groundwater that is considered "brackish". The most recent samples collected at Roy Kizer Spring have higher than normal conductivity readings. The range of conductivity is even higher (between 1000 µS/cm to 3000 µS/cm) at the Great Hills Golf Course resulting from the combined use of reclaimed water and Trinity Aquifer water.

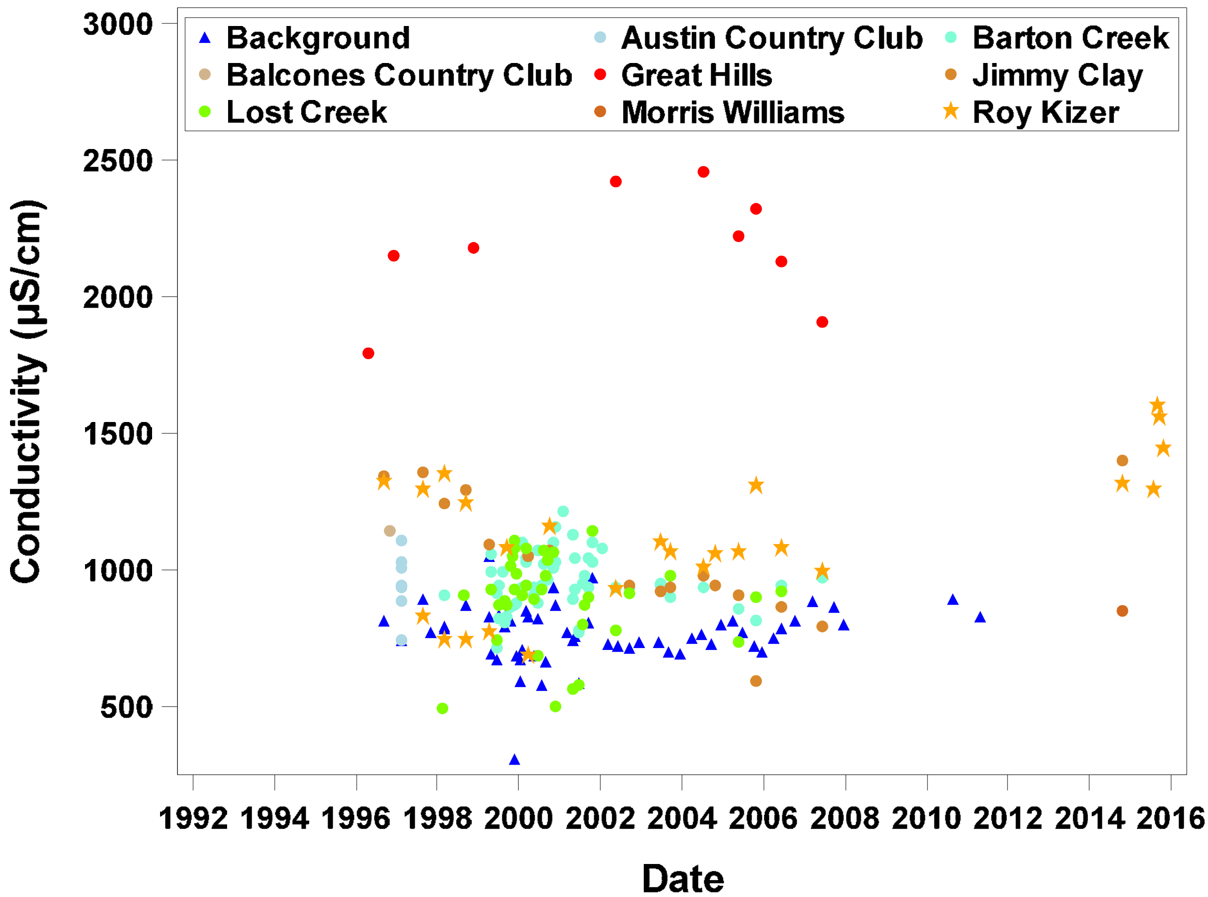

Figure 24: Conductivity at springs near Austin area golf courses (COA data). Most golf courses assessed that irrigate with reclaimed water generally have conductivity values above 770 µS/cm, the background condition for the purposes of this analysis. The high values at Great Hills results from the mixed use of reclaimed water and Trinity Aquifer groundwater.

Nitrate+nitrite nitrogen concentrations at golf course influenced springs in Austin range from 0.1 to 30 mg/L (Figure 25). Antecedent weather, irrigation rate, and spring discharge are all potential confounding factors that contribute to high variability in the data set. However, the mean nitrate+nitrite concentration at Avery Ranch Spring (background) was 2.26 mg/L (95% CI = 1.98 - 2.53 mg/L) which is significantly lower than the mean nitrate+nitrite concentration at Roy Kizer Spring (mean = 6.19 mg/L, 95% CI = 4.61 – 7.76 mg/L) (t-test with unequal variance, $p = 0.0001$). Roy Kizer Spring displays very high concentrations of nitrate in the most recent samples.

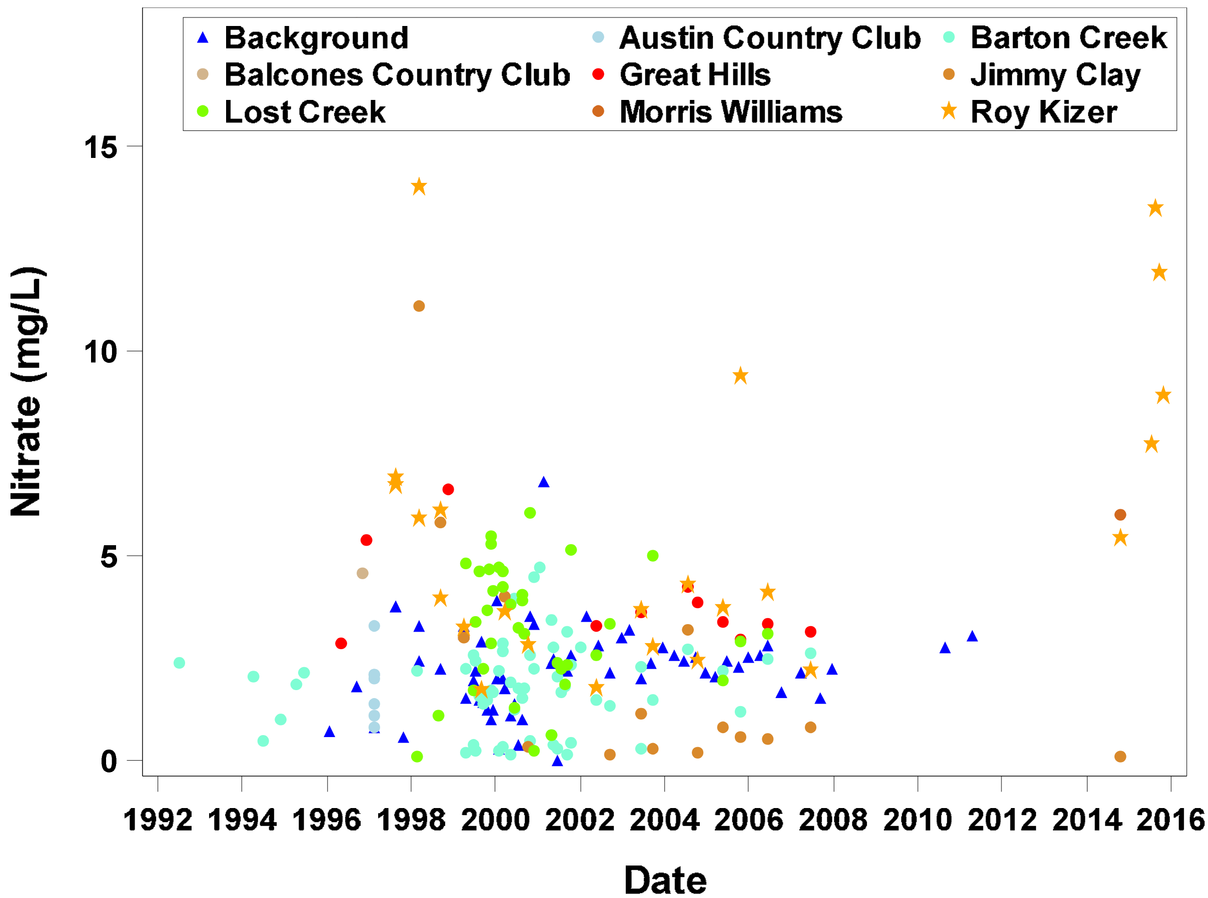

Figure 25: Nitrate+nitrite at springs near Austin area golf courses, showing that some of the highest concentrations were collected at Roy Kizer Spring during this study (2014-2015). Background concentrations for the purposes of this analysis, collected at Avery Ranch golf course (no reclaimed water irrigation), are generally below 5 mg/L.

A bivariate plot of conductivity and nitrate+nitrite nitrogen shows a positive linear relationship between increasing conductivity measurements and nitrate+nitrite nitrogen at the background golf course spring. This indicates that conductivity and nitrate+nitrite nitrogen may increase together (Figure 26). The ellipse shown in the bottom left corner of Figure 26 illustrates the zone of the 95% interval for background conductivity versus nitrate+nitrite. Data that is outside of the 95% ellipse may be considered to be different from background. There are a substantial amount of data points collected at Roy Kizer and Jimmy Clay golf courses that are outside this 95% ellipse and may be considered as different (in this case higher) than background conditions.

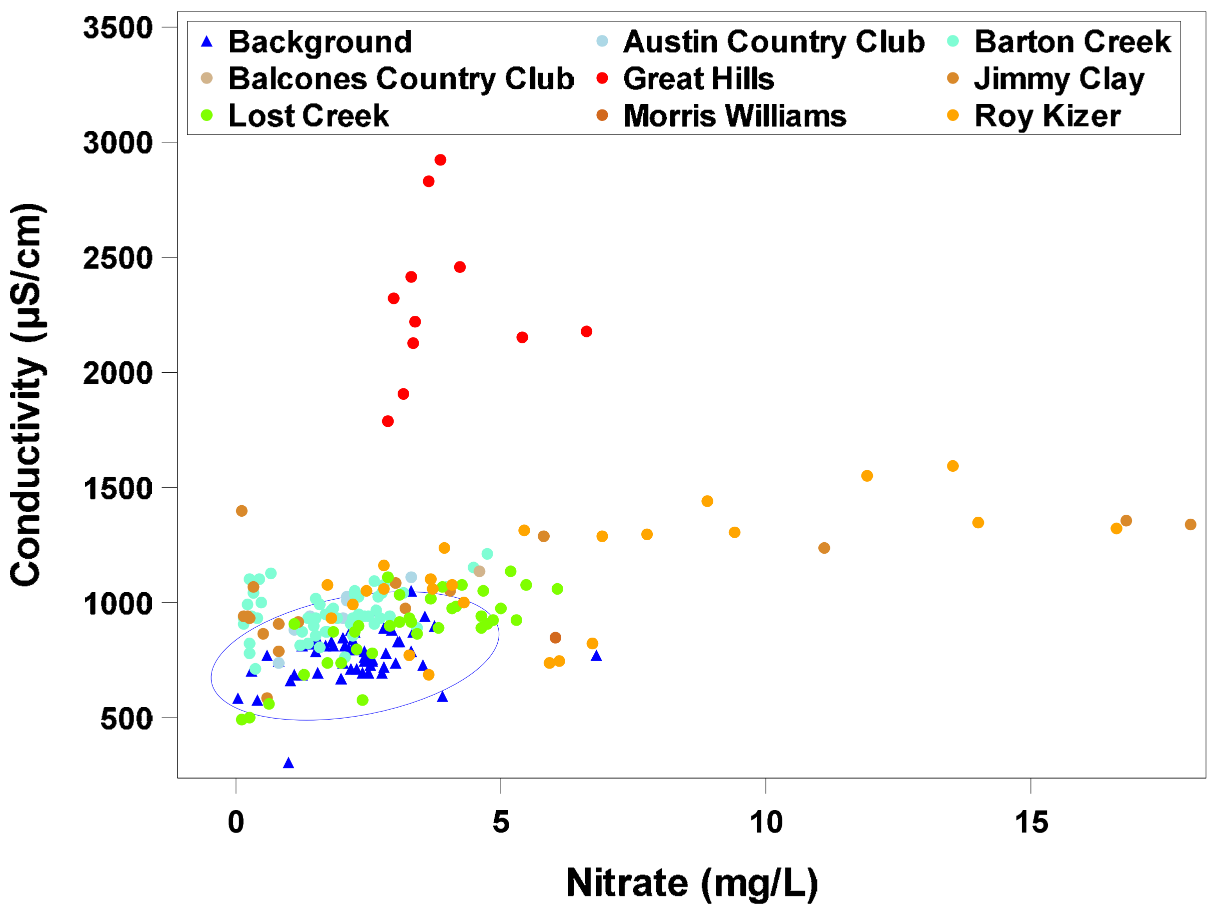

Figure 26: Conductivity versus nitrate in springs affected by golf courses. Background conditions for the purpose of this analysis are those at springs that do not include reclaimed water irrigation in the springshed, such as Avery Ranch. The ellipse shows the 95% interval for background conductivity versus nitrate. A majority of Roy Kizer, Jimmy Clay and Morris Williams values are outside the 95% background, suggesting that they are different from non-reclaim irrigated or upper gradient golf course springs.

<u>Antecedent Rainfall</u>

Rainfall data within the Tannehill watershed showed that all sample events were conducted under non-storm influenced conditions, although three of the four sampling events at Bartholomew Park followed fairly recently after rain events of more than 0.5 inches (Figure 27). Rainfall data within the Williamson watershed showed that the 15 October 2014 and 24 September 2015 sampling events followed rain events in which the total rainfall over the watershed was over 0.5 inches. There was little to no rain one month prior to the remaining sampling events at Clay/Kizer (Figure 28). The monthly irrigation volume at Clay/Kizer was highest for the 23 July 2015 and 27 August 2015 sampling events. Sample collection was attempted on 20 October 2015 for the Clay/Kizer sites, but Williamson Creek was not flowing at this time and no water column or benthic samples were collected.

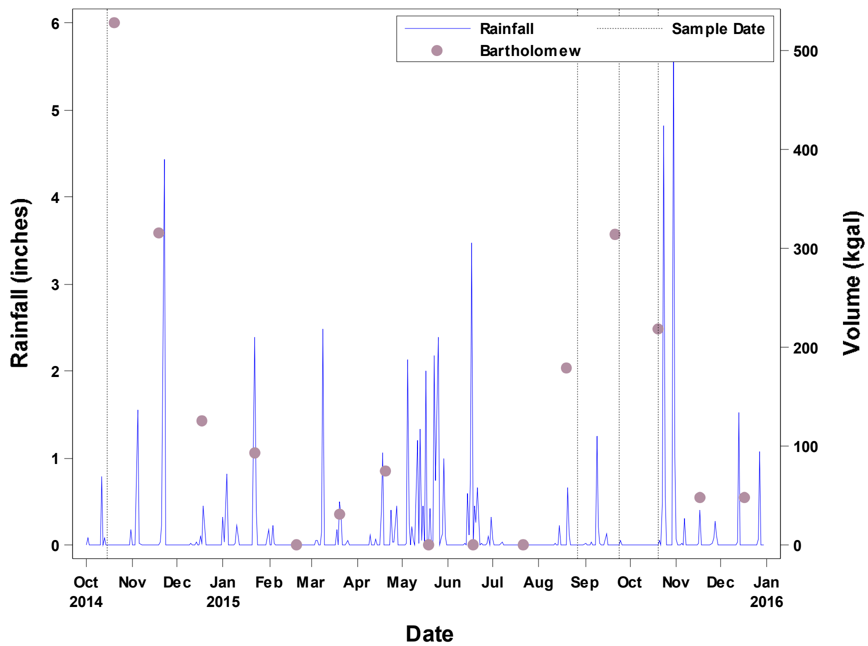

Figure 27: Rainfall (inches), Bartholomew Park irrigation volume (kgal) from October 2014 to December 2015. Dashed lines represent sampling events.

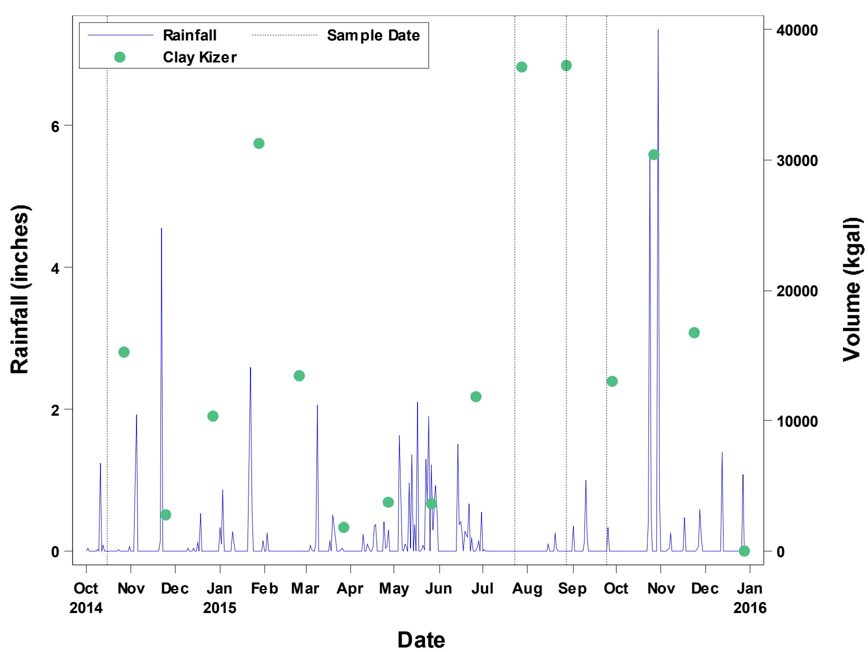

Figure 28: Rainfall (inches), Clay/Kizer irrigation volume (kgal) from October 2014 to December 2015. Dashed lines represent sampling events.

As Morris Williams Golf Course (Figure 29) also lies within the Tannehill watershed, rainfall and sampling patterns are similar to that of Bartholomew Park described previously. The monthly irrigation volume at Morris Williams was highest for the 27 August 2015 sampling event.

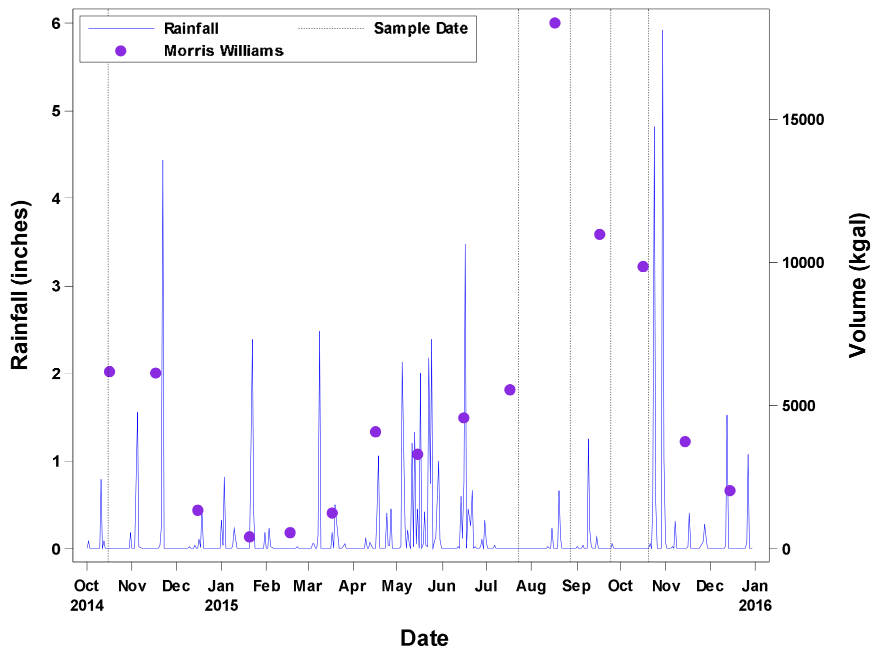

Figure 29: Rainfall (inches), Morris Williams irrigation volume (kgal) from October 2014 to December 2015. Dashed lines represent sampling events.

Nitrogen Isotopes

Lab analysis of the stable δ^{15}nitrogen and δ^{18} oxygen isotope ratios of nitrate collected during the October 25, 2014, sampling event revealed that all sites with sufficient nitrate for isotope analysis plotted in the biogenic range using common source fields by Kendall (1988). This suggests that the source of nitrogen was manure or wastewater (Figure 34). Similar isotopic comparisons have been used to identify potential wastewater effluent impacts to Austin area waterbodies by the United States Geological Survey (Mahler et al. 2011). There was no indication that the nitrogen in the study water bodies was originating from precipitation or fertilizer application. Both upstream and downstream sites on Waller Creek plotted in the biogenic range, possibly indicating leaking wastewater infrastructure upstream of the Hancock Golf Course.

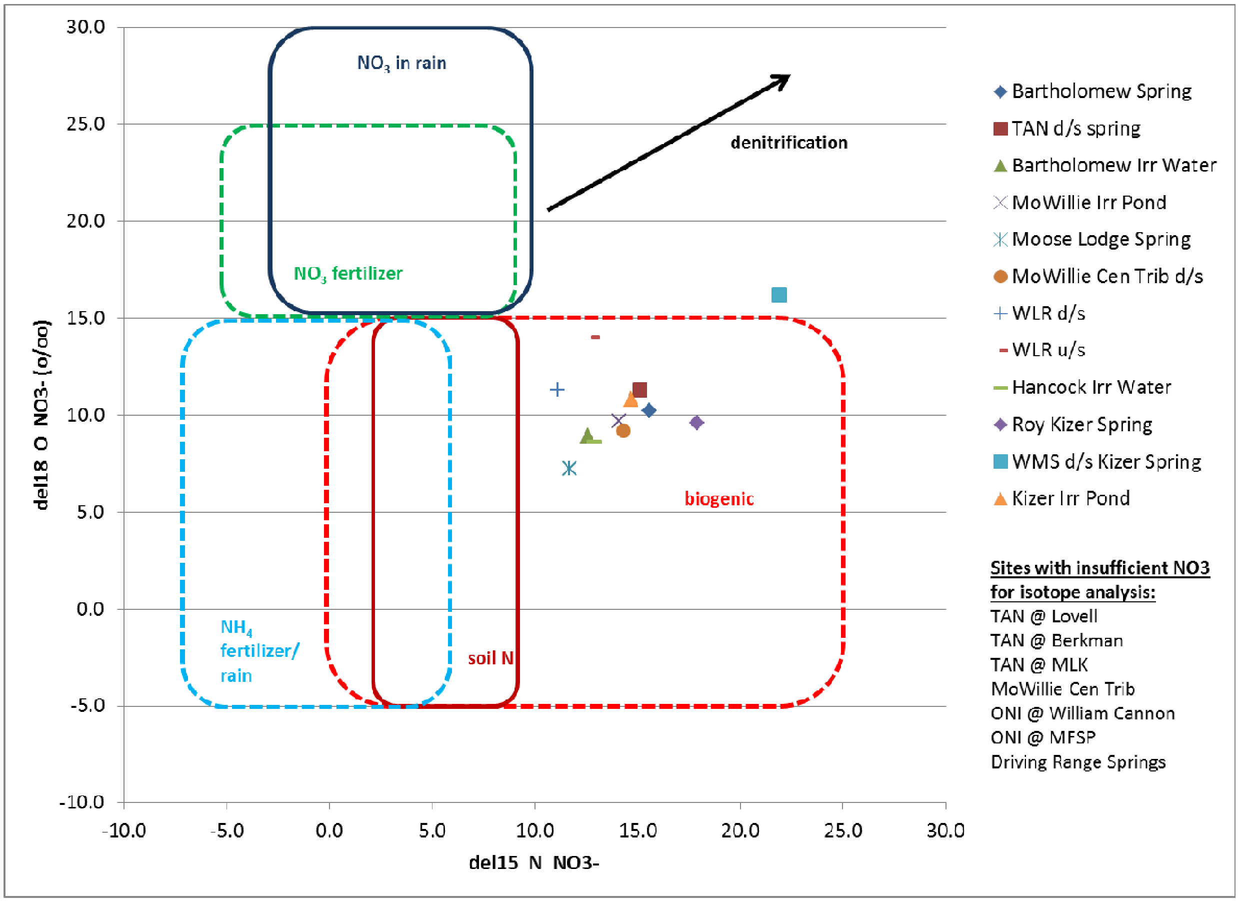

Figure 34: Nitrogen/Oxygen stable isotope ratio plot for study sites. Source boundaries adapted from Kendall (1998).

Conclusions

Using the conservation of mass, a conceptual model was established to determine whether there was a discernible impact from reclaimed water on adjacent surface water and groundwater resources. This model generated three hypotheses (see Methods section), which were tested against statistical intervals of data collected at each of three City of Austin facilities irrigating with reclaimed water. Furthermore, this conceptual model allowed for a more precise model, pHREEQc, which incorporated the interaction of geochemical processes into the model. The pHREEQc model provided predictions on the composition of downstream water given a certain mixture of upstream water and reclaimed water. This information was also used to verify the validity of the conceptual model and as an indication of the appropriateness of the hypothesis chosen. Finally, additional data was provided supporting the model and the conclusions presented below:

- Confidence intervals in surface water indicate that nitrate+nitrite and ions including sulfate, alkalinity, chloride, sodium, magnesium, potassium, and calcium are significantly higher in the downstream surface water samples at 2 of the 4 sites, Bartholomew and Roy Kizer (Figure 5, 9, and 11), but not significantly higher at Morris Williams mainstem and ambiguous for Morris Williams central tributary. Information from benthic nutrient ratios (discussed below) at Morris Williams central tributary removed this ambiguity.

- The benthic C:P confidence intervals exhibited a significant decrease from upstream to downstream sites indicating degradation downstream of reclaim water irrigation areas. While there was no significant difference in benthic C:N ratios from upstream to downstream, the probability of the benthic C:N ratios to be lower at downstream sites was high (0.89) and more samples would be necessary to validate indicate a significant decrease from upstream to downstream. In addition, benthic C:P and C:N ratios from only 2 of the 13 paired (upstream/downstream) samples were higher downstream than upstream (Figures 31 and 32). There was no significant difference in benthic chlorophyll *a* (mass per unit area) from upstream to downstream even though the nutrients for growth were more readily available to algae downstream of the irrigation. Thus, there was not a significant increase in biomass upstream to downstream observed in this study although confounding factors such as available sunlight (i.e., accounting for variable canopy cover at the study sites) were not evaluated in this analysis.

- The difference in benthic C:P and C:N ratios were most prominent in the mainstem of Tannehill Creek upstream and downstream of Morris Williams Golf Course. The differences in water column nutrients between the upstream and downstream locations at Morris Williams were the most ambiguous with this being the only paired location where there was not more nitrate+nitrite downstream of the irrigation.

- Piper plots of chemical facies indicate downstream waters generally trend from the upstream conditions toward the reclaimed water conditions indicating an influence of the reclaimed water on surface water resources (Figures 20, 21, and 23).

- The computer model, pHREEQc, estimated that about 40% of the downstream water at Bartholomew Park was from reclaimed water, validating the results from the confidence intervals at Bartholomew Park. The variability in the data at Roy Kizer could not reproduce a similarly precise estimate from pHREEQc of the reclaimed water contribution on the downstream section. Estimates of reclaimed water contribution on downstream sections of Morris Williams did not indicate an impact on the surface water, but benthic ratios show a clear uptake of the nutrients into the algal biomass.

- Samples from springs at the golf course study sites where reclaimed water is irrigated generally show higher conductivity than background conditions (Figures 24 and 26), consistent with previous local evaluations (Hiers and Herrington 2007). More specifically, conductivity collected at the spring adjacent to Roy Kizer is significantly higher than background conditions.

- Nitrate+nitrite concentrations at the spring impacted by Roy Kizer Golf Course are significantly higher than background concentrations, consistent with previous local evaluations (Hiers and Herrington 2007) and other U.S. Geological Survey studies (Pruitt et al. 1988, Katz et al. 2009). In fact, some of the highest nitrate+nitrite concentrations ever observed by the City of Austin in springs were collected at the Roy Kizer Golf Course. Of the 2,693 nitrate+nitrite samples collected from springs, the 10 highest values are all from Jimmy Clay and Roy Kizer, one of which was recently collected at Roy Kizer (Figures 22 and 25).

- Nitrogen and oxygen isotopes of nitrate for all sites with sufficient nitrate for analysis indicated that nitrogen is originating from biogenic (manure or wastewater) sources (Figure 34) during the October 2014 sampling event. Nitrogen in Waller Creek upstream of Hancock Golf Course also yielded a biogenic signature.

Based on these findings, the hypothesis that there is an impact (Hypothesis 2) to the receiving stream either on the surface water or the benthic algal stoichiometry that is likely attributable to the irrigation of reclaimed water is validated. Irrigation of reclaimed water appears to be inadvertently degrading the quality of adjacent surface water and groundwater resources based on the weight of evidence evaluated in this study.

Recommendations

1. Reclaimed water irrigation should not occur adjacent to waterways to avoid unintended adverse water quality impacts. A protective setback distance to avoid adverse impacts has not yet been quantitatively determined by the City of Austin Watershed Protection Department. The Critical Water Quality Zone (City of Austin Land Development Code Chapter 25-8-92), Erosion Hazard Zone (City of Austin Land Development Code Chapter 27-7-2, Drainage Criteria Manual Appendix E) and/or the City of Austin fully-developed floodplain boundaries should be considered as protective buffers in which no reclaimed water irrigation should occur, consistent with existing City of Austin policies and land development regulations to limit anthropogenic disturbance in these areas.

2. If irrigation of reclaimed water cannot be adjusted on a specific site so that it does not occur within the Critical Water Quality Zone and/or City of Austin fully-developed floodplain (e.g., potentially due to the width of these zones relative to the total size of a specific parcel), then site-specific characteristics (e.g., soils, geology, topography, vegetation) should be evaluated on a case-by-case basis to determine appropriate protective setbacks.

3. If it is determined that current irrigation of reclaimed water on public parks adjacent to waterways is unavoidable, then measures should be implemented over time to minimize adverse impacts to surface water. Mitigation measures may include, but are not limited to, revised riparian vegetation management practices that maximize nutrient uptake, sprinkler head adjustments, and additional monitoring to identify potential adjustments to irrigation rates or schedule while meeting turf grass needs. That additional monitoring could also improve the statistical intervals developed in this report.

4. Additional sampling as described in the Methods section of this report is recommended to increase the resolution of benthic C:N ratios upstream and downstream of irrigation sites to more conclusively determine if impacts are present for this parameter.

5. Benthic chlorophyll *a* concentrations (mass per unit area) were too variable to discern an upstream to downstream statistical pattern. Additional explanatory variables like canopy cover need to be accounted for when using benthic chlorophyll *a* as a measure of degradation in similar scenarios.

Discussion

Reclaimed water is a priority demand-side water conservation strategy for the City of Austin, as recognized in the Austin Water Resource Planning Task Force Report to City Council (July 2014, austintexas.gov/page/austin-water-resource-planning-task-force). Reclaimed water use not only reduces the discharge of treated effluent to the Colorado River, but also reduces the withdrawal of high quality raw water from Lake Austin and Lake Travis. The Austin Water Utility has 74 active metered reclaimed water customers, four bulk fill stations, and more than 50 miles of reclaimed water distribution pipelines already installed. Reuse of City of Austin reclaimed water constitutes approximately 3% of total wastewater volume treated. For site plan applications submitted on or after May 1, 2015, the City of Austin mandates connection of new commercial development to the reclaimed water distribution system if the development is within 250 ft of a reclaimed water main. Thus, applying restrictions on current or future reclaimed water irrigation should be carefully considered.

This report proposes restrictions on reclaimed water irrigation within the floodplain, CWQZ or EHZ (see Recommendations). Planning staff within the City of Austin Watershed Protection Department conducted four geographic information system (GIS) analyses of the potential implications of the Recommendations of this report on existing, planned, and new potential reclaimed water customers. These analyses utilized Travis County Appraisal District (TCAD) parcel boundaries within the actual Austin Water Utility water service area (water pressure zone). Parcel boundaries were intersected with City of Austin fully-developed floodplain (floodplain), Critical Water Quality Zone (CWQZ) and Erosion Hazard Zone (EHZ) boundaries.

<u>Scenario 1, all parcels within Austin Water Utility actual water service area</u>
This scenario assessed the percent area of 207,433 individual TCAD parcels in the actual Austin Water water service area within the floodplain, CWQZ and EHZ on an individual parcel basis. Of the 207,433 parcels assessed, there were 175,501 parcels (84.6% of total) with no area either within the floodplain, CWQZ, or EHZ. Approximately 99.19% of parcels have less than 3% of the area within the parcel boundaries falling within the floodplain, CWQZ or EHZ. Less than 0.02% of parcels are estimated to have 75% or more of the total parcel area falling within the floodplain, CWQZ or EHZ. Thus, on a citywide basis the restrictions on reclaimed water irrigation proposed in the Recommendations section of this report would have a minimal impact future reclaimed water use (Table 5).

Table 5. Analysis of the most restrictive (maximum) impact of limitation on reclaimed water irrigation on all parcels within the Austin Water Utility actual water service area.

Maximum Percent of Parcel Affected (Bin)	# of Parcels within the Bin	% of Total Number of Parcels within the Bin
0	175,501	84.61
less than 1%	28,500	13.74
1%-2%	1,205	0.58
2%-3%	539	0.26
3-4%	377	0.18
4-5%	243	0.12
5-6%	170	0.08
6-7%	128	0.06
7-8%	89	0.04
8-9%	96	0.05
9-10%	73	0.04
10-25%	343	0.17
25-50%	100	0.05
50-75%	26	0.01
75-100%	43	0.02

<u>Scenario 2, potential new reclaimed water customer impact</u>
This scenario assessed the potential impact of the restrictions on reclaimed water irrigation proposed in the Recommendations section of this report on potential new reclaimed water customers as identified by Austin Water in February 2015. The maximum pervious area of the 31 TCAD parcels within the floodplain, CWQZ or EHZ was assessed. Two of the 31 potential new customer parcels had no pervious

area (as defined by City of Austin Environmental Criteria Manual) within the parcel boundaries. The majority (96.7%) of identified potential new customers had less than 2% of their pervious areas falling within the floodplain, CWQZ or EHZ. The maximum impact was 5.4% of the pervious area, occurring on one parcel (Table 6).

Table 6. Analysis of most restrictive (maximum) impact of limitation on reclaimed water irrigation on the pervious area of parcels identified as potential new reclaimed water customers (as of February 2015).

Maximum Percent of Pervious Area Within Parcel Affected (Bin)	# of Parcels within Bin	% of Total # of Parcels
No Pervious Area	2	6.45
No impact	18	58.06
Less than 1%	8	25.81
1-2%	2	6.45
5-6%	1	3.23

Scenario 3, potential impact to existing reclaimed water customers

This scenario intersected TCAD parcel boundaries for 45 existing Austin Water reclaimed water customers (as identified in February 2015) with the floodplain, CWQZ and EHZ boundaries. The majority of existing reclaimed water customer parcels (64.4%) had no pervious area within the floodplain, CWQZ or EHZ. Only 11.1% of existing customer parcels had 50% of their total pervious area within the floodplain, CWQZ or EHZ.

Table 7. Analysis of most restrictive (maximum) impact of limitation on reclaimed water irrigation on the pervious area of parcels for existing reclaimed water customers (as of February 2015).

Maximum Percent of Pervious Area with Parcel Affected (Bin)	# of Parcels within Bin	% of Total # of Parcels
No impact	29	64.44
Less than 10%	2	4.44
10-20%	4	8.89
20-30%	1	2.22
30-40%	2	4.44
40-50%	2	4.44
50-60%	1	2.22
60-70%	0	0.00
70-80%	2	4.44
80-90%	0	0.00
90-100%	2	4.44

Scenario 4, parcels within 100 ft of a current or proposed reclaimed water main

This scenario identified parcels within the Austin Water actual water service area located within 100 ft of a current or proposed reclaimed water distribution main. The pervious (irrigable) area for these 6,940 parcels also falling within the floodplain, CWQZ or EHZ was assessed. The majority of parcels (81%) within 100 ft of an existing or reclaimed water distribution main had all of their pervious area falling within the floodplain, CWQZ or EHZ. Approximately 6.2% of parcels had no pervious area outside of the floodplain, CWQZ or EHZ. Approximately 10.6% of parcels within 100 ft of an existing or planned reclaimed water distribution main would not be able to irrigate reclaimed water on 50% or more of their pervious area as a result of restrictions proposed in the Recommendations section (Table 8).

Table 8. Analysis of most restrictive (maximum) impact of limitation on reclaimed water irrigation on the pervious area of parcels within 100 ft of an existing or planned reclaimed water distribution main.

Maximum % of Pervious Area within Parcel Affected (Bin)	# of Parcels within Bin	% of Total # of Parcels
0%	5624	81.04
less than 1%	48	0.69
1-10%	129	1.86
10-20%	118	1.70
20-30%	104	1.50
30-40%	97	1.40
40-50%	80	1.15
50-60%	80	1.15
60-70%	74	1.07
70-80%	78	1.12
80-90%	73	1.05
90-100%	435	6.27

Acknowledgements

This initial sampling event was completed with the assistance of multiple City of Austin Parks and Recreation Department staff that facilitated access to the park and golf course study locations. Additionally, Dan Pedersen with Austin Water provided background information on the use of reclaimed water at these locations, and provided reclaimed water sampling information. The City of Austin Watershed Protection Department expresses sincere appreciation to these individuals for their valuable assistance with this project.

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Appendix A Paired Differences

Table A.1: Confidence Intervals of the Mean Paired Differences in Concentrations (mg/L, unless otherwise noted) between Downstream and Upstream Samples in Bartholomew Park

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
DISSOLVED OXYGEN	-5.6	-1.6	2.0
pH (standard units)	-0.35	-0.10	0.15
Ammonia	-0.14	0.02	0.18
Nitrate	1.04	1.76	2.45
TKN	-0.19	0.11	0.39
Total Nitrogen	1.20	1.84	2.48
Orthophosphorus	-0.032	0.009	0.046
Phosphorus	-0.023	0.023	0.069
Alkalinity	96.2	106.9	117.8
Chloride	16.5	41.0	63.5
Sodium	12.9	29.9	45.7
Magnesium	3.0	5.0	6.8
Calcium	32.4	55.0	74.2
Potassium	0.3	1.2	2.1
Sulfate	5.8	30.5	57.5
Fluoride	-0.04	0.00	0.04
Strontium	0.09	0.19	0.27

Table A.2: Confidence Intervals of the Mean Paired Differences in Concentrations (mg/L, unless otherwise noted) between Downstream and Upstream Samples in Morris Williams (main stem)

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
DISSOLVED OXYGEN	-4.9	-1.4	1.9
pH (standard units)	-0.34	-0.13	0.09
Ammonia	-0.06	0.08	0.25
Nitrate	-1.02	-0.39	0.27
TKN	0.11	0.39	0.66
Total Nitrogen	0.32	0.95	1.58
Orthophosphorus	-0.028	0.010	0.043
Phosphorus	-0.017	0.025	0.067
Alkalinity	-68.7	-59.0	-49.3
Chloride	-9.0	11.1	33.8
Sodium	-7.3	7.0	22.7
Magnesium	-1.5	0.2	1.9
Calcium	-43.8	-26.3	-5.3
Potassium	-0.2	0.6	1.4
Sulfate	-14.4	11.5	36.3
Fluoride	-0.05	-0.01	0.03
Strontium	-0.16	-0.09	-0.01

Table A.3: Confidence Intervals of the Mean Paired Differences in Concentrations (mg/L, unless otherwise noted) between Downstream and Upstream Samples in Morris Williams (central tributary)

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
DISSOLVED OXYGEN	-2.0	1.6	5.1
pH (standard units)	0.47	0.67	0.86
Ammonia	-0.19	-0.02	0.12
Nitrate	0.16	0.79	1.45
TKN	-0.21	0.07	0.34
Total Nitrogen	-0.50	0.80	2.10
Orthophosphorus	-0.008	0.026	0.069
Phosphorus	-0.004	0.035	0.084
Alkalinity	1.6	11.2	21.0
Chloride	-1.6	18.6	39.2
Sodium	-3.9	10.2	25.1
Magnesium	-1.4	0.2	2.0
Calcium	-1.3	17.0	35.0
Potassium	-1.0	-0.2	0.7
Sulfate	0.7	24.2	47.1
Fluoride	-0.02	0.02	0.05
Strontium	-0.02	0.05	0.13

Table A.4: Confidence Intervals of the Mean Paired Differences in Concentrations (mg/L, unless otherwise noted) between Downstream and Upstream Samples in Roy Kizer

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
DISSOLVED OXYGEN	-4.8	-1.3	2.1
pH (standard units)	-0.64	-0.43	-0.20
Ammonia	-0.17	0.01	0.18
Nitrate	2.33	3.20	4.00
TKN	0.00	0.31	0.65
Total Nitrogen	-0.78	3.62	8.02
Orthophosphorus	-0.044	0.005	0.043
Phosphorus	-0.053	0.011	0.056
Alkalinity	28.0	40.0	52.2
Chloride	18.5	48.9	74.4
Sodium	15.9	37.2	55.3
Magnesium	3.3	5.6	7.7
Calcium	11.6	36.3	58.8
Potassium	2.7	3.9	5.0
Sulfate	11.0	40.0	72.6
Fluoride	-0.01	0.03	0.08
Strontium	-0.09	0.00	0.10

Appendix B Confidence Intervals of the Mean

Table B.1: Confidence Intervals of the Mean in Concentrations (mg/L) at Bartholomew Park

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
Upstream			
Orthophosphorus	<DL	<DL	<DL
Phosphorus	<DL	0.02	0.14
Nitrate	<DL	0.09	3.56
TKN	0.056	0.53	0.99
Alkalinity	69.64	102.4	134.6
Chloride	<DL	16.02	34.64
Sodium	<DL	12.56	27.11
Magnesium	<DL	3.56	7.99
Calcium	25.50	44.46	63.56
Potassium	1.50	2.426	3.36
Sulfate	<DL	16.44	33.28
Fluoride	0.14	0.37	0.59
Downstream			
Orthophosphorus	<DL	.01	.02
Phosphorus	<DL	0.04	0.26
Nitrate	<DL	1.32	3.65
TKN	0.15	0.51	0.87
Alkalinity	195.4	224.9	251.7
Chloride	52.70	63.11	73.18
Sodium	38.29	48.29	58.09
Magnesium	6.05	8.98	11.86
Calcium	86.22	101.00	115.00
Potassium	3.38	3.95	4.51
Sulfate	46.42	56.18	65.61
Fluoride	0.21	0.36	0.52
Reclaimed Water			
Orthophosphorus	4.22	4.56	4.90
Phosphorus	4.53	4.69	4.84
Nitrate	25.6	28.6	31.5
TKN	0.3	0.7	1.2
Alkalinity	<DL	27.7	62.2
Chloride	107.5	120.5	132.7
Sodium	114.9	127.6	139.4
Magnesium	30.5	34.1	37.6
Calcium	32.8	50.4	67.9
Potassium	14.1	14.8	15.5
Sulfate	173.0	185.1	196.4
Fluoride	1.9	2.1	2.3

Table B.2: Confidence Intervals of the Mean in Concentrations (mg/L) at Morris Williams (main stem)

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
Upstream			
Orthophosphorus	<DL	<DL	<DL
Phosphorus	<DL	<DL	0.03
Nitrate	<DL	0.71	2.87
TKN	<DL	0.26	0.62
Alkalinity	217.8	245.6	271.1
Chloride	25.59	34.99	44.56
Sodium	16.09	25.22	34.52
Magnesium	3.11	5.80	8.51
Calcium	97.00	110.70	123.50
Potassium	1.30	1.83	2.36
Sulfate	29.08	38.15	46.98
Fluoride	0.21	0.34	0.48
Downstream			
Orthophosphorus	<DL	0.01	0.03
Phosphorus	<DL	0.05	0.17
Nitrate	<DL	0.34	2.75
TKN	0.251	0.60	0.96
Alkalinity	138.40	161.80	184.10
Chloride	25.22	38.41	51.37
Sodium	16.71	27.10	37.42
Magnesium	2.35	5.40	8.50
Calcium	61.38	75.18	88.54
Potassium	1.742	2.392	3.055
Sulfate	26.26	38.19	50.01
Fluoride	0.15	0.31	0.47
Reclaimed Water			
Orthophosphorus	4.22	4.56	4.90
Phosphorus	4.53	4.69	4.84
Nitrate	25.6	28.6	31.5
TKN	0.3	0.7	1.2
Alkalinity	<DL	27.6	55.8
Chloride	107.5	120.5	132.7
Sodium	114.9	127.6	139.4
Magnesium	30.5	34.1	37.6
Calcium	32.8	50.4	67.9
Potassium	14.1	14.8	15.5
Sulfate	173.0	185.1	196.4
Fluoride	1.9	2.1	2.3

Table B.3: Confidence Intervals of the Mean in Concentrations (mg/L) at Morris Williams (central tributary)

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
Upstream			
Orthophosphorus	<DL	<DL	<DL
Phosphorus	<DL	0.02	0.04
Nitrate	4.55	5.73	6.95
TKN	7.16	7.32	7.48
Alkalinity	<DL	1.07	2.31
Chloride	0.17	0.30	0.44
Sodium	129	216	291
Magnesium	6.13	30.44	52.21
Calcium	11.05	25.31	38.80
Potassium	2.68	4.98	7.27
Sulfate	38.29	96.77	145.30
Fluoride	1.50	2.45	3.39
Downstream			
Orthophosphorus	<DL	0.05	0.15
Phosphorus	<DL	0.07	0.19
Nitrate	0.53	1.76	3.00
TKN	0.19	0.32	0.45
Alkalinity	135	223	297
Chloride	18.82	43.03	65.90
Sodium	17.57	32.22	46.09
Magnesium	2.83	5.08	7.34
Calcium	49.63	111.10	160.70
Potassium	1.34	2.28	3.19
Sulfate	16.99	48.96	79.44
Fluoride	0.34	0.39	0.45
Reclaimed Water			
Orthophosphorus	4.22	4.56	4.90
Phosphorus	4.53	4.69	4.84
Nitrate	25.6	28.6	31.5
TKN	0.3	0.7	1.2
Alkalinity	<DL	27.6	55.8
Chloride	107.5	120.5	132.7
Sodium	114.9	127.6	139.4
Magnesium	30.5	34.1	37.6
Calcium	32.8	50.4	67.9
Potassium	14.1	14.8	15.5
Sulfate	173.0	185.1	196.4
Fluoride	1.9	2.1	2.3

Table B.4: Confidence Intervals of the Mean in Concentrations (mg/L) at Roy Kizer

Parameter Name	Bayes LCI	Bayes Median	Bayes UCI
Upstream			
Orthophosphorus	<DL	0.01	0.02
Phosphorus	<DL	0.02	0.04
Nitrate	<DL	1.11	5.45
TKN	<DL	0.19	0.77
Alkalinity	161.7	207.1	247.8
Chloride	5.36	39.09	75.13
Sodium	1.54	24.39	49.62
Magnesium	4.63	8.59	12.68
Calcium	64.91	94.38	120.20
Potassium	0.38	1.96	3.67
Sulfate	15.05	49.23	79.48
Fluoride	0.11	0.31	0.53
Downstream			
Orthophosphorus	<DL	<DL	0.03
Phosphorus	<DL	0.02	0.05
Nitrate	<DL	3.50	7.13
TKN	0.01	0.46	0.93
Alkalinity	198.8	238.8	274.5
Chloride	46.44	78.99	107.20
Sodium	33.82	54.55	73.82
Magnesium	9.43	12.81	16.32
Calcium	93.12	121.30	143.70
Potassium	4.17	5.62	7.07
Sulfate	46.77	80.44	108.50
Fluoride	0.16	0.34	0.53
Reclaimed Water			
Orthophosphorus	0.26	1.59	2.92
Phosphorus	1.32	1.81	2.29
Nitrate	9.23	13.26	16.73
TKN	0.79	1.32	1.77
Alkalinity	63.2	102.1	138.3
Chloride	59.23	97.33	124.90
Sodium	60.82	85.62	104.40
Magnesium	20.84	24.59	27.95
Calcium	19.40	42.66	67.07
Potassium	13.72	15.20	16.61
Sulfate	32.15	61.11	87.58
Fluoride	0.98	1.17	1.35

Appendix C

Benthic algae carbon to phosphorus (C:P) ratios, carbon to nitrogen (C:N) ratios, and benthic algae chlorophyll *a* collected upstream and downstream of each reclaim irrigation site.

Date	Site	Benthic C:P Ratio		Benthic C:N Ratio		Benthic chlorophyll *a* (mg/m^2)	
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
15-OCT-14	Bartholomew	11.13	10.45	2.15	1.59	35.81	57.32
	Clay/Kizer: Onion	17.66	6.08	2.56	2.17	14.30	8.40
	Clay/Kizer: Williamson	26.27	9.78	8.30	1.91	9.30	41.90
	Hancock	7.95	9.79	1.35	1.80	26.47	65.82
	Morris Williams	15.34	7.76	2.29	1.87	80.40	90.02
23-JUL-15	Clay/Kizer: Williamson	14.18	11.48	1.49	0.85	136.31	104.46
	Morris Williams	23.08	11.93	1.68	1.66	25.34	54.78
27-AUG-15	Bartholomew	10.11	12.02	1.79	1.53	72.61	105.02
	Clay/Kizer: Williamson	14.85	16.21	2.48	1.73	57.04	47.98
	Morris Williams	21.11	16.23	2.10	1.79	167.02	98.37
24-SEP-15	Bartholomew	17.50	10.91	1.40	1.85	31.99	78.70
	Clay/Kizer: Williamson	15.23	13.46	0.50	0.65	109.41	112.95
	Morris Williams	19.39	4.65	0.73	0.46	93.70	54.78
20-OCT-15	Bartholomew	18.18	8.15	1.81	1.57	30.29	223.64
	Morris Williams	21.77	11.99	1.96	1.77	57.75	52.94

Appendix D

Differences between total nitrogen in the water column, benthic C:P, benthic C:N, and benthic chlorophyll *a* for each sampling event were analyzed (Figures D1-D4). C:P ratios and C:N ratios are thought to be lower in streams where nutrients are available for uptake at high concentrations, which can result in low water column concentrations of nutrients because the periphyton has acquired the nutrients.

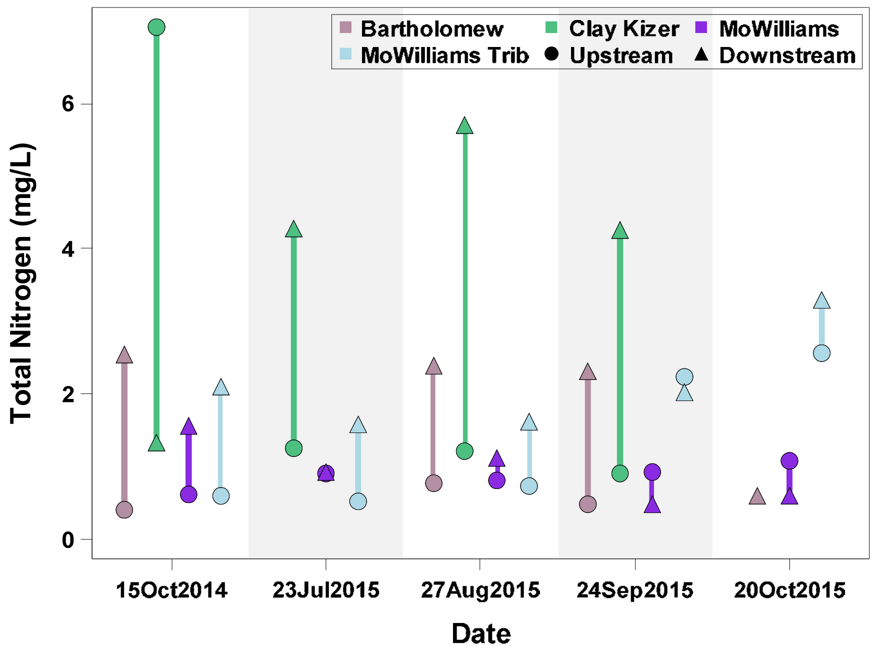

Figure D.1: Upstream and downstream total nitrogen (mg/L) collected from Bartholomew Park, Roy Kizer, and Morris Williams surface water beginning in October 2014 to December 2015.

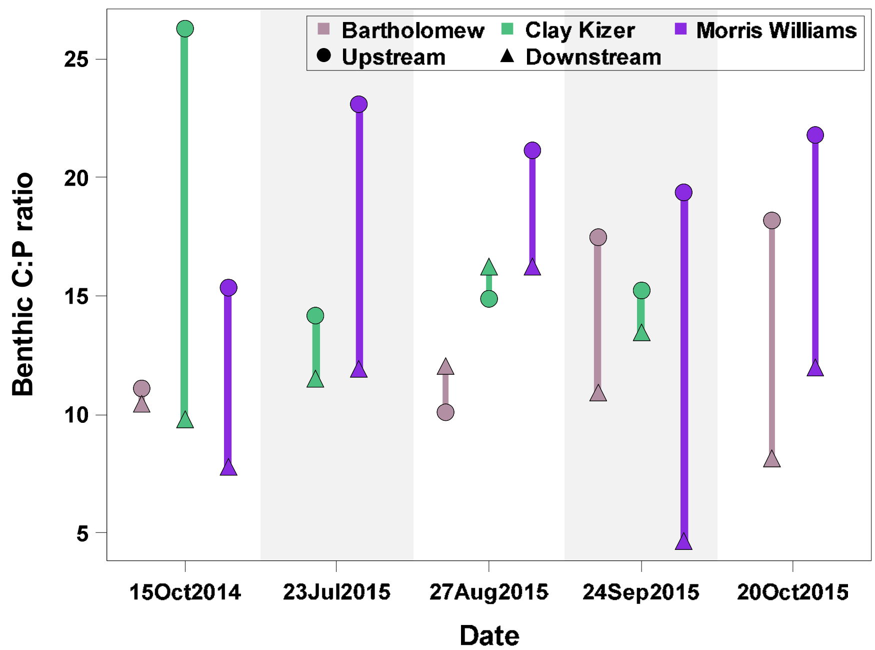

Figure D.2: Upstream and downstream benthic C:P collected from Bartholomew Park, Roy Kizer, and Morris Williams beginning in October 2014 to December 2015.

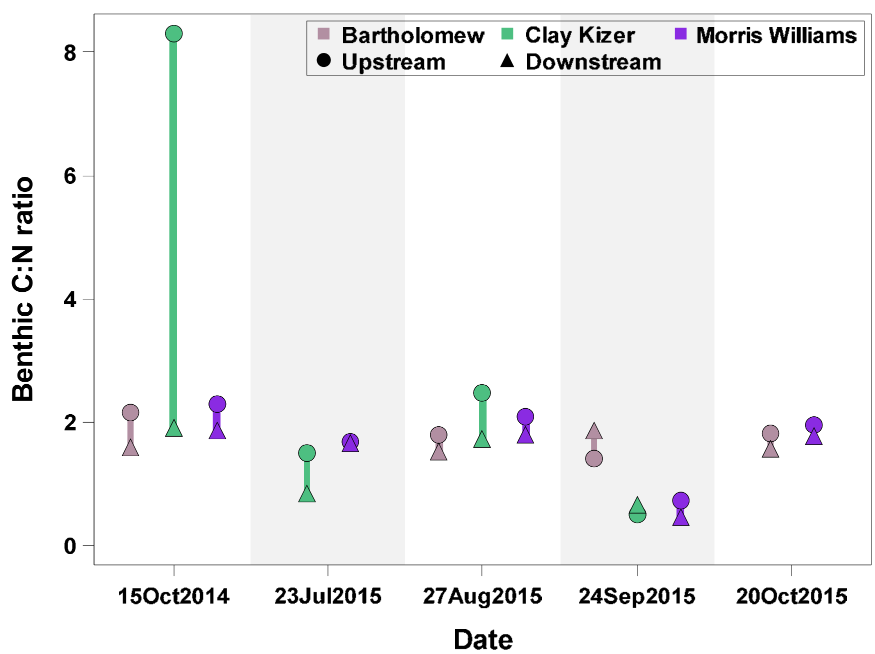

Figure D.3: Upstream and downstream benthic C:N collected from Bartholomew Park, Roy Kizer, and Morris Williams beginning in October 2014 to December 2015.

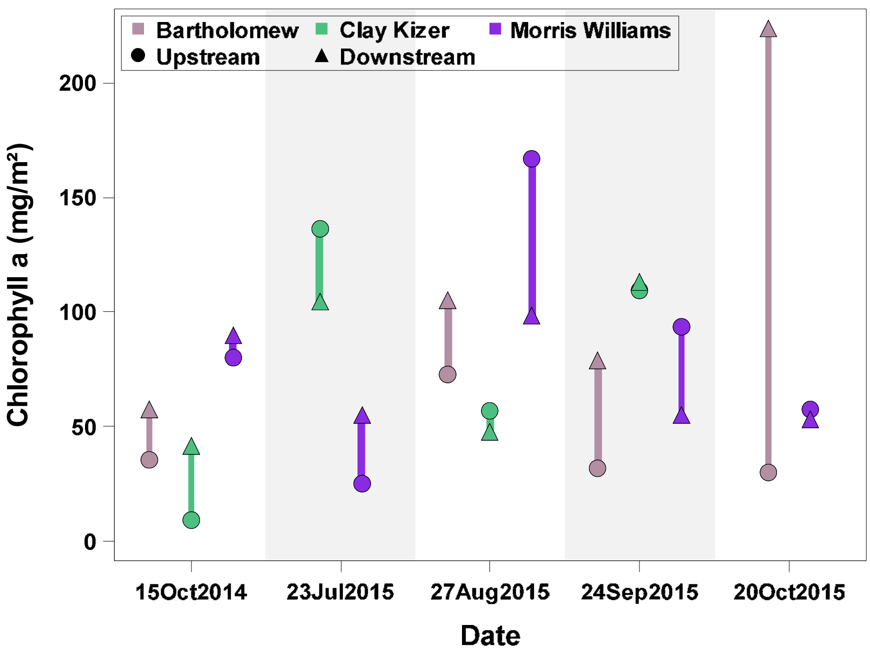

Figure D.4: Upstream and downstream benthic chlorophyll *a* (mg/m^2) collected from Bartholomew Park, Roy Kizer, and Morris Williams beginning in October 2014 to December 2015.

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

DR-18-01, October 2017

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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 (Porras 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.

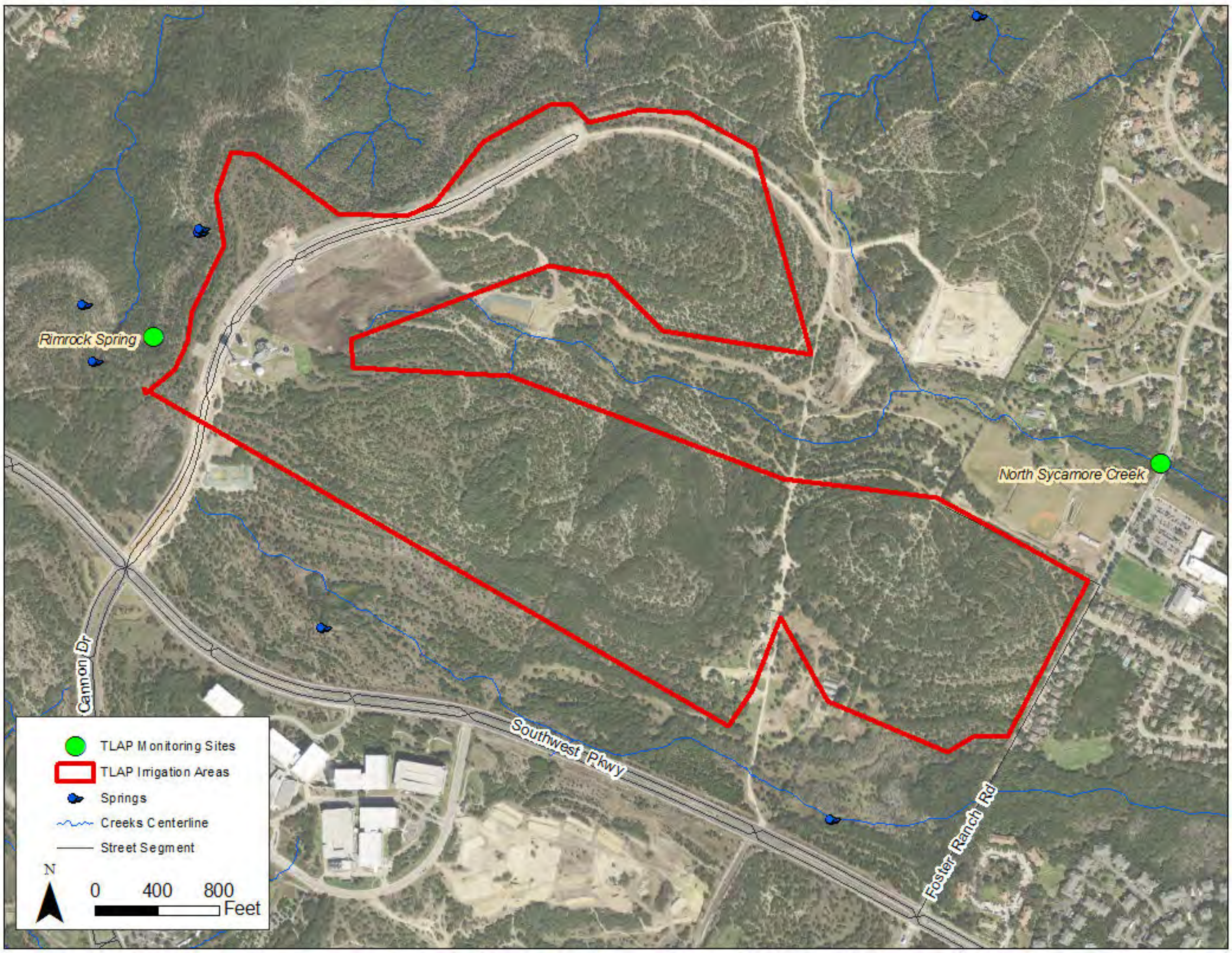

Figure 1. Rimrock Spring and North Sycamore at Foster Ranch sample sites at the future TLAP field Travis County Municipal Utility District (MUD) No. 4.

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.

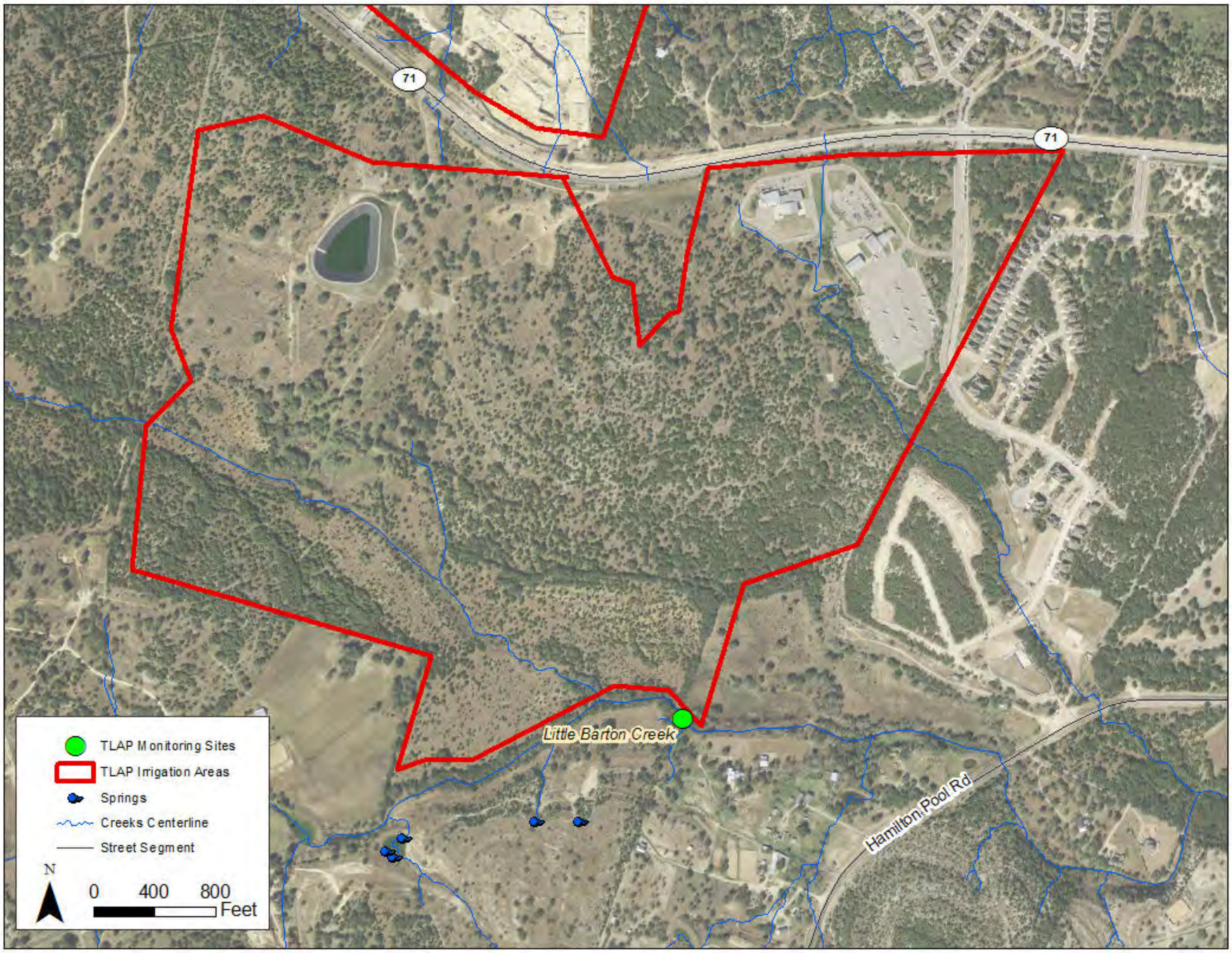

Figure 2. Little Barton Creek Upstream of Hamilton Pool sample site at Lazy Nine MUD 1A and Sweetwater Austin Properties LLC.

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.

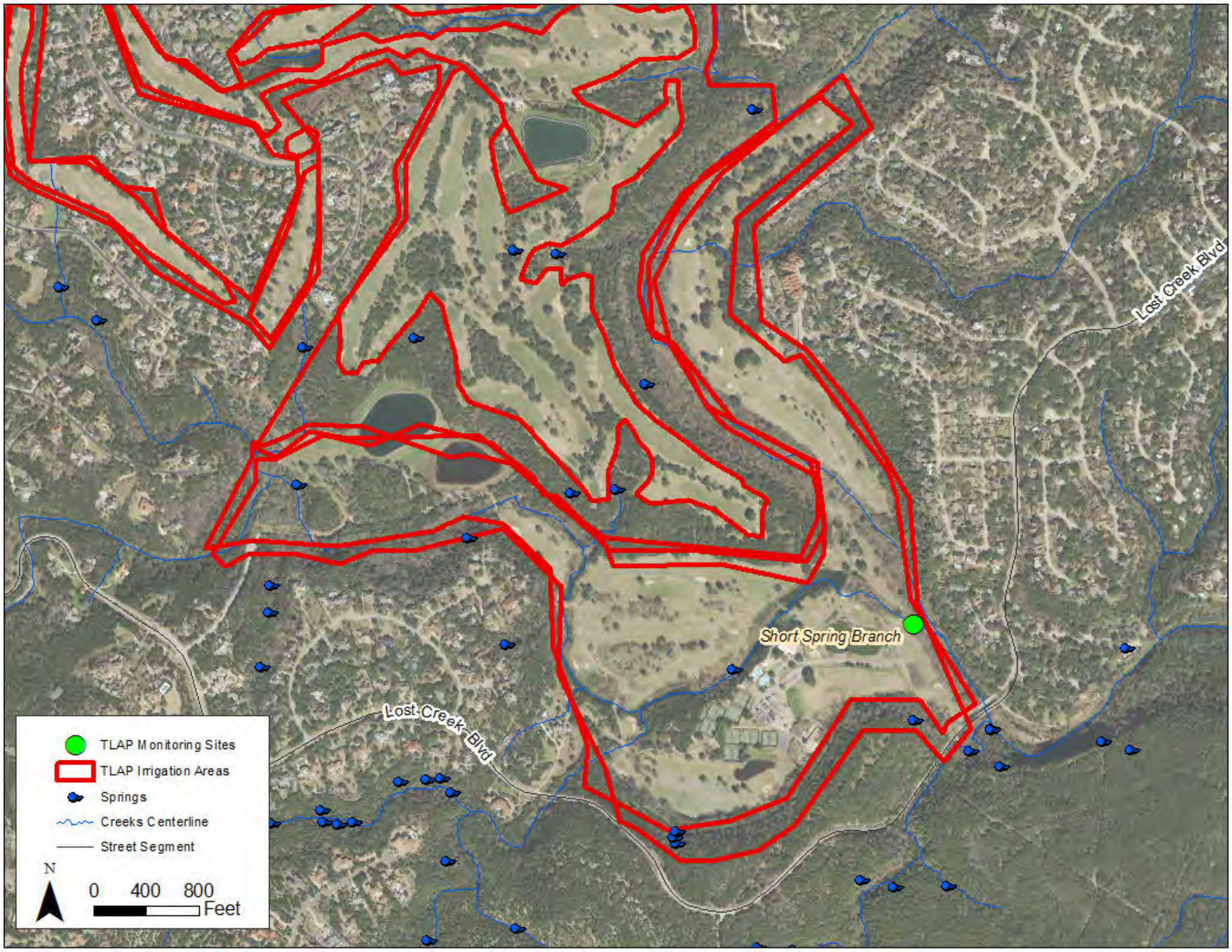

Figure 3. Short Spring Branch sample site at Lost Creek Wastewater Treatment Facility.

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.

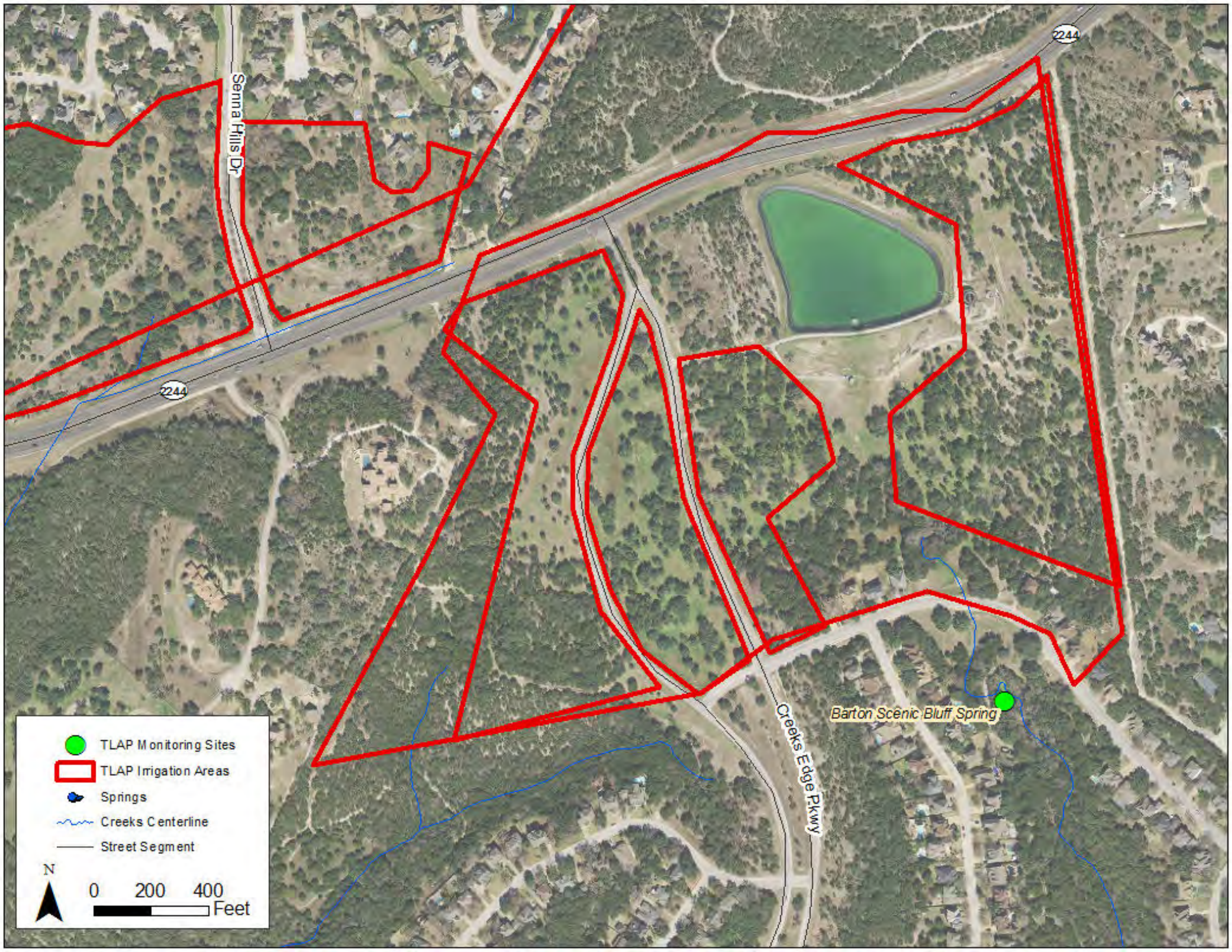

Figure 4. Barton Scenic Bluff Spring sample site at Barton Creek West.

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	*Escherichia coli* (*E. coli*)
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, mu 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
E. coli	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
E. coli	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 $^{87}Sr/^{86}Sr$ 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 strontainite ($SrCO_3$), 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 ($^{87}Sr/^{86}Sr$) 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 crystalize 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 $^{87}Sr/^{86}Sr$ ratio. The ratio $^{87}Sr/^{86}Sr$ in rocks varies greatly with rock type and age. The average $^{87}Sr/^{86}Sr$ ratio for rock types range from 0.702 to 0.716 (Michener and Lajtha 2007). The $^{87}Sr/^{86}Sr$ ratio of modern seawater and precipitation is about 0.7092 (Åberg et al. 1989, Capo et al. 1998). The $^{87}Sr/^{86}Sr$ of groundwater will be similar to the concentration seen in the underlying rock, so strontium isotopes ($^{87}Sr/^{86}Sr$) 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, $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ 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 (Porras 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 $^{87}Sr/^{86}Sr$ 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 Count MUD No.4.

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Attachment 2

Upper Barton Creek Gain/Loss Study at Shield Ranch

Upper Barton Creek Gain/Loss Study at Shield Ranch

RR-24-01
January 2024

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Abstract

The Trinity and Edwards Aquifers are regionally connected karst systems that provide crucial freshwater resources and endangered salamander habitat in semi-arid Central Texas. Trinity Aquifer springs in the Contributing Zone of the Edwards Aquifer supply baseflow to creeks, including Barton Creek. Contributing Zone creeks flow across the Edwards Aquifer Recharge Zone where they lose water to the Edwards Aquifer and – in the Barton Springs Segment of the Edwards Aquifer (BSEA) – discharge at Barton Springs and Cold Springs. As Central Texas becomes more urbanized and native landscapes become smaller, rarer, and more disconnected within the BSEA contributing watersheds, protecting land to maintain high quality baseflow in creeks and at Barton Springs is increasingly urgent. Shield Ranch, the largest conservation easement on Barton Creek, protects nearly 7,000 acres (approximately 10%) of the watershed and over six miles of the creek. This study characterized groundwater-surface water interactions along Barton Creek through Shield Ranch using standard handheld velocimeter methods during three separate gauging events from June-July 2019. The results demonstrated that Barton Creek within Shield Ranch is a net gaining stream with some local flow loss into alluvium within the creek channel. Notable gaining reaches and visible spring and seep zones were recorded. As is typical for Barton Creek during hotter and drier weather, baseflow decreased throughout the summer with correspondingly smaller net total gains across the ranch. As the overall system dried during the summer, the declining groundwater inputs indicated that the springs are gravity fed and the local water table of the Trinity Aquifer drops seasonally. Climatological changes, which will likely exacerbate the seasonal drop in the water table, coupled with increasing population growth and urbanization in the Hill Country west of Austin will continue to threaten water quality and potential natural recharge to the system, making land conservation efforts like those at Shield Ranch imperative for the future of Central Texas.

Keywords: Gain/Loss, Barton Creek, Shield Ranch, springs, Trinity Aquifer

Introduction

The City of Austin Watershed Protection Department (WPD), in partnership with Shield Ranch and the Barton Springs Edwards Aquifer Conservation District (BSEACD), conducted a gain/loss study to characterize groundwater and surface water interactions on Barton Creek throughout Shield Ranch in the summer of 2019. Shield Ranch is managed for conservation and environmental protection and is the largest conservation easement in the Barton Creek watershed, protecting nearly 7,000 acres (approximately 10%) of the watershed and over six miles of the creek (Figure 1). Conservation easements on the Ranch are held by the Nature Conservancy and the City of Austin.

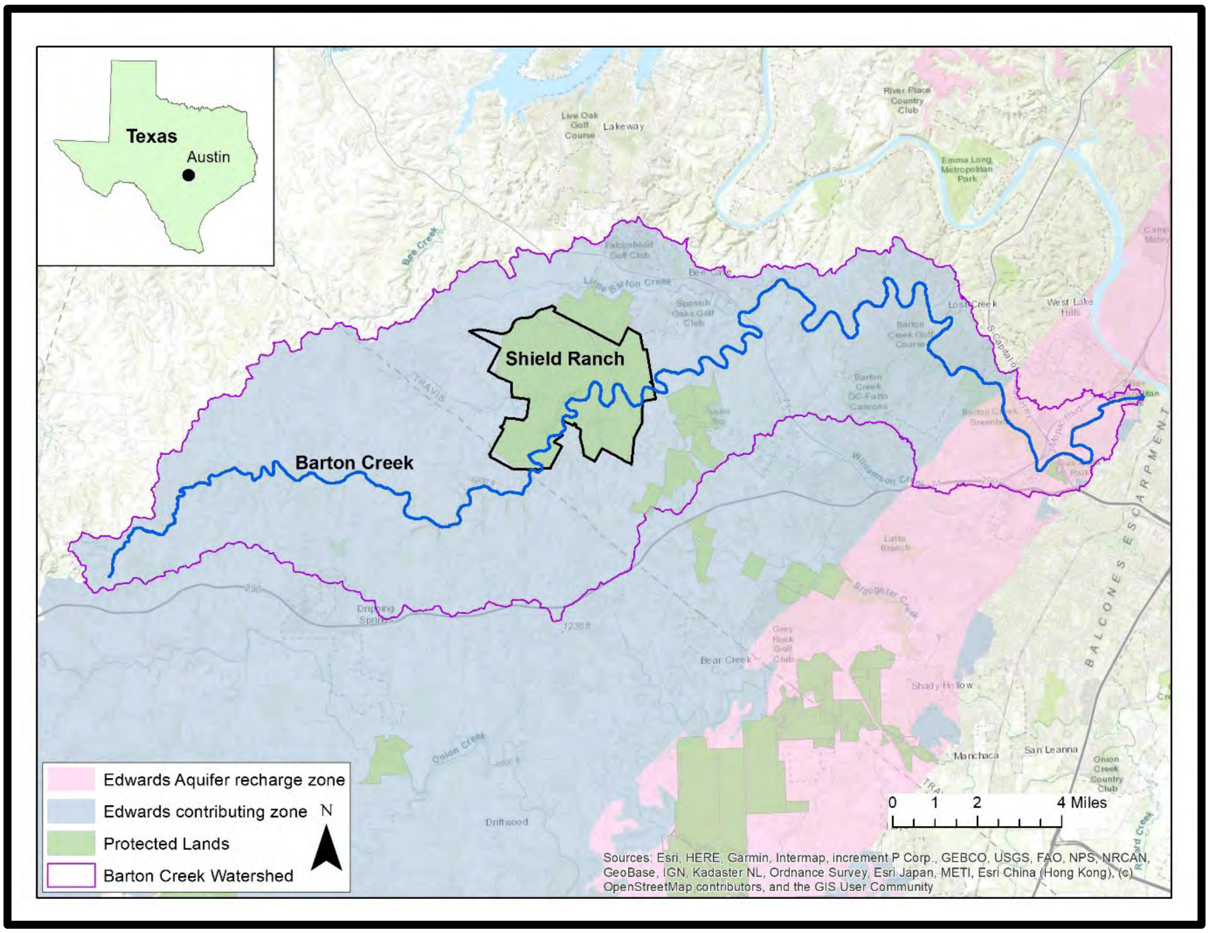

Figure 1.Shield Ranch and the Barton Creek watershed near Austin, Texas.

Trinity Aquifer-fed springs provide the dominant source of baseflow to Barton Creek, which flows downstream across the Barton Springs Edwards Aquifer (BSEA) Recharge Zone and past Barton Springs to the Colorado River. Under recharge conditions, creek water recharges the BSEA and discharges at Barton Springs and Cold Springs, both of which contribute to the total discharge of the Colorado River. The Glen Rose Limestone, which partially comprises the upper and middle Trinity Aquifer, is exposed at the surface throughout most of Shield Ranch including the channel of Barton Creek and its tributaries, although non-contiguous Edwards Limestone is also present on some isolated hilltops on site. This area of the Trinity Aquifer is also referred to as the “Contributing Zone” of the Edwards Aquifer, since rain that falls in this area contributes to creeks that flow downstream to the Recharge Zone where the Edwards Limestone is exposed at the surface. Shield Ranch's size and location on Barton Creek in the Contributing Zone makes it important for both the water quality and quantity reaching the BSEA Recharge Zone downstream (Figure 1).

Barton Creek is a prime example of the hydrogeological connectivity between the Trinity Aquifer and the BSEA. Interactions between the Trinity and Edwards Aquifers were underestimated in the past but have become a topic of great interest to hydrogeologists and water resource managers in Central Texas. Of interest are both groundwater-surface water interactions and subsurface connectivity between the two aquifers; subsurface connectivity, while beyond the scope of this study, is introduced in Gary et al. (2011). Recent studies within the BSEA Contributing Zone on Onion Creek and the Blanco River (Hunt et al. 2017, Smith et al. 2014) as well as other creeks within the San Antonio Edwards Aquifer (Green et al. 2011) have demonstrated significant flow loss and recharge to the Trinity Aquifer. The volume of spring contributions (gains) and flow losses via recharge has not been as thoroughly characterized in the Barton Creek Watershed upstream of the Recharge Zone. Some stream gauging occurred on Barton Creek in the past which showed net flow gains upstream of the Recharge Zone (COA 1997), but comprehensive gain/loss studies have not characterized the groundwater-surface water interactions across discrete reaches of the creek during varying streamflow conditions.

This study, performed as an intern-led project over 3 sampling events in summer 2019, is an initial look at the volume of spring (groundwater) influence on the creek within Shield Ranch as well as the influence of the creek on groundwater through gain/loss measurements and analysis. The site-specific information provided herein on the groundwater-surface water interactions in one of Austin's premier high-quality creeks can support the management and protection of this valuable resource. Future studies may compare this baseline information with more urbanized watersheds or examine different, smaller, or larger portions of Barton Creek.

Methods

A gain/loss study uses a series of stream discharge measurements gauged during baseflow to quantify the gains and/or losses of flow along a stream reach. The measurements are taken as close to the same time as possible in order to evaluate spatial flow variations rather than temporal variations. The gain/loss analysis (Equation 1), essentially a water balance, is a basic mathematical and geospatial technique used frequently by hydrologists and hydrogeologists to evaluate groundwater – surface water interactions (e.g. Braun and Gryzb 2015, Hunt et al 2017). Unaccounted for gains and/or losses indicate features like springs or sinkholes submerged within the channel.

Equation 1. Gain/loss analysis modified from Braun and Grzyb (2015) pg. 18:
The difference between inflows and outflows, referred to as the gain (positive/increase in flow) or loss (negative/decrease in flow), Q_{GL}, is estimated as:

$$Q_{\mathrm{GL}} = Q_D - Q_U - I + D - R + E$$

where:

Q_D is measured streamflow at the downstream boundary of the reach
Q_U is measured streamflow at the upstream boundary of the reach
I is measured or estimated inflows from tributaries
D is diversions from the reach
R is return flows to the reach
E is estimated evaporation losses
(Units of all variables in cubic feet per second.)

Barton Creek at Shield Ranch has no diversions or return flows. Staff analysis assumed that the diffuse inputs to baseflow in the stream were from springs. Evaporation was checked using the regional standard (LCRA daily measurement); however, the value was low enough to be within the margin of error for the stream gauging measurements (+/- 10%) and therefore was assumed to be negligible.

WPD staff conducted three separate stream gauging events along Barton Creek within Shield Ranch on June 20-21, July 10-11, and July 22-24, 2019. Sixteen sites (Figure 2) along Barton Creek within Shield Ranch were selected for flow measurements based on tributary confluences and access, with three of these sites added after the first gauging event. To quantify tributary contributions, flow was measured either: 1) both upstream and downstream of the tributary on the main stem or 2) on the tributary itself and on the main stem either upstream or downstream of the tributary. During the second stream gauging event, BSEACD staff also measured flow at more widely spaced intervals along the length of Barton Creek up and downstream of Shield Ranch, but all upstream of the Edwards Aquifer Recharge Zone.

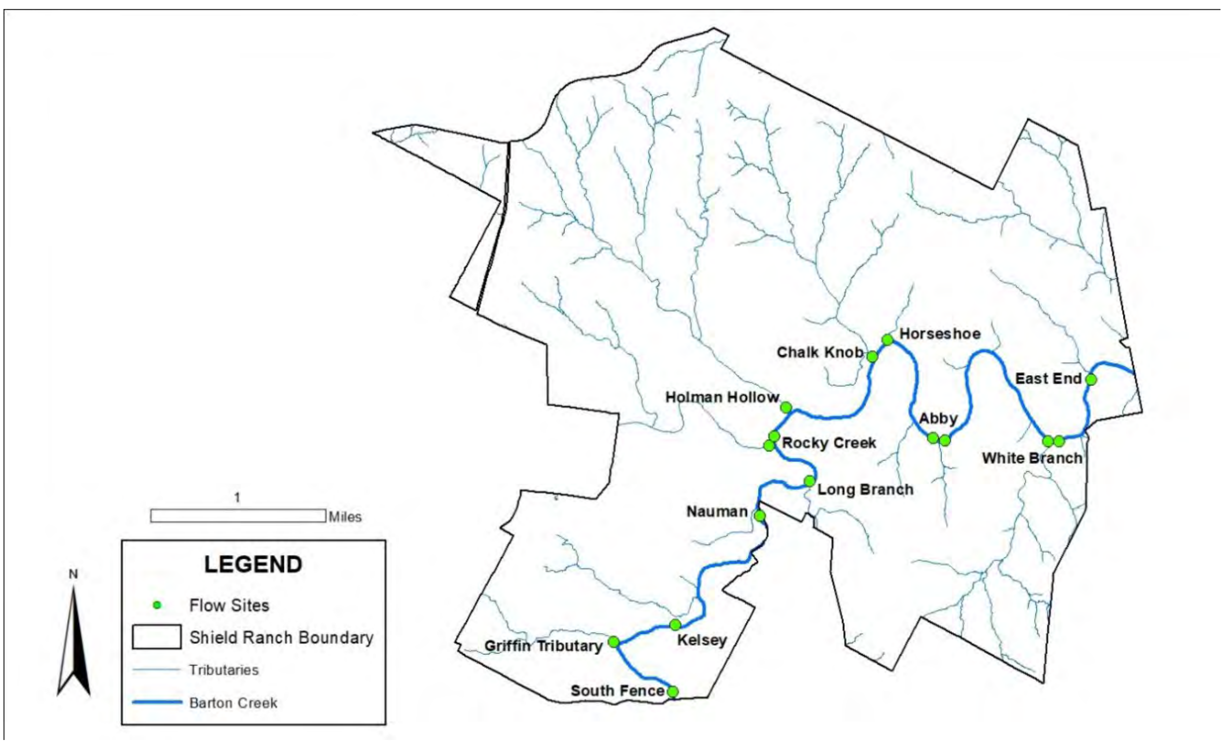

Figure 2 Measurement sites near key confluences on Shield Ranch

Stream gauging methods and techniques followed methods detailed in Turnipseed and Sauer (2010). Staff measured flow using a handheld Acoustic Doppler Velocimeter (ADV): a FlowTracker at sites with water depths greater than 0.3 ft (most sites, see Photo 1) and a Marsh McBirney flow meter at shallow sites (<0.3 feet deep). The FlowTracker calculated total discharge using the midsection method (SonTek 2007, Turnipseed and Sauer 2010). Some tributaries could not be measured due to very low flow, so flow was visually estimated.

Photo 1: Collecting a flow measurement using a Flowtracker ADV.

For quality assurance, during each event field staff collected at least two flow measurements at each site until two measurements were within 10% of each other. Staff averaged these measurements to calculate a discharge value for each site, reported in Table 1 and Figure 4 in the Results section. Net gains across Shield Ranch were calculated by subtracting discharge at the upstream-most station from discharge at the downstream-most station (i.e., to include tributary contributions) and then tributary contributions and main-stem groundwater contributions were considered separately.

Results

As the study progressed during dry, hot weather with minimal rainfall, overall baseflow in Barton Creek declined and the number of tributaries with measurable flow decreased over subsequent events as well (Figure 3). While gauging was planned for baseflow conditions, minor rainfall occurred on day two of the third sampling event, reducing the validity of these measurements. A significant storm event (see large peak in discharge on June 25) occurred between Events 1 and 2. This event was substantial enough to cause small changes to channel geomorphology (e.g. noticeable scouring or gravel deposition near some sites) between Events 1 and 2 as observed in staff field notes.

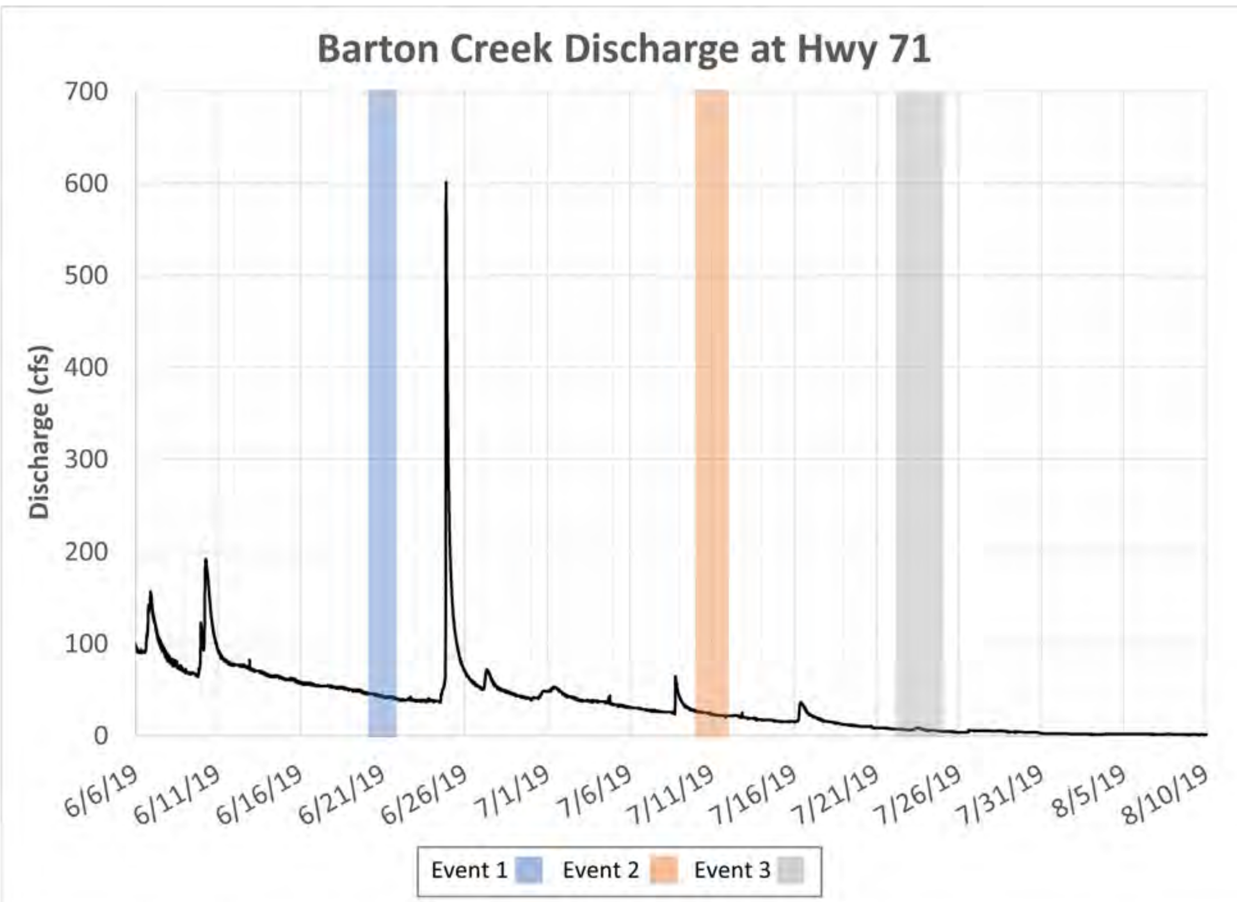

Figure 3: Discharge at USGS gaging station 08155200 on Barton Creek at Hwy 71 from June-July 2019. Each of the gauging events conducted in this study are highlighted. All measurements from Events 1 and 2 were taken under baseflow conditions, and baseflow decreased throughout the summer.

All three sampling events showed that Barton Creek is a net gaining stream across Shield Ranch, with measured creek flow increases of 52 – 162% (including tributary contributions) from the upstream end of the ranch to the downstream end (Figure 4 and Table 1).

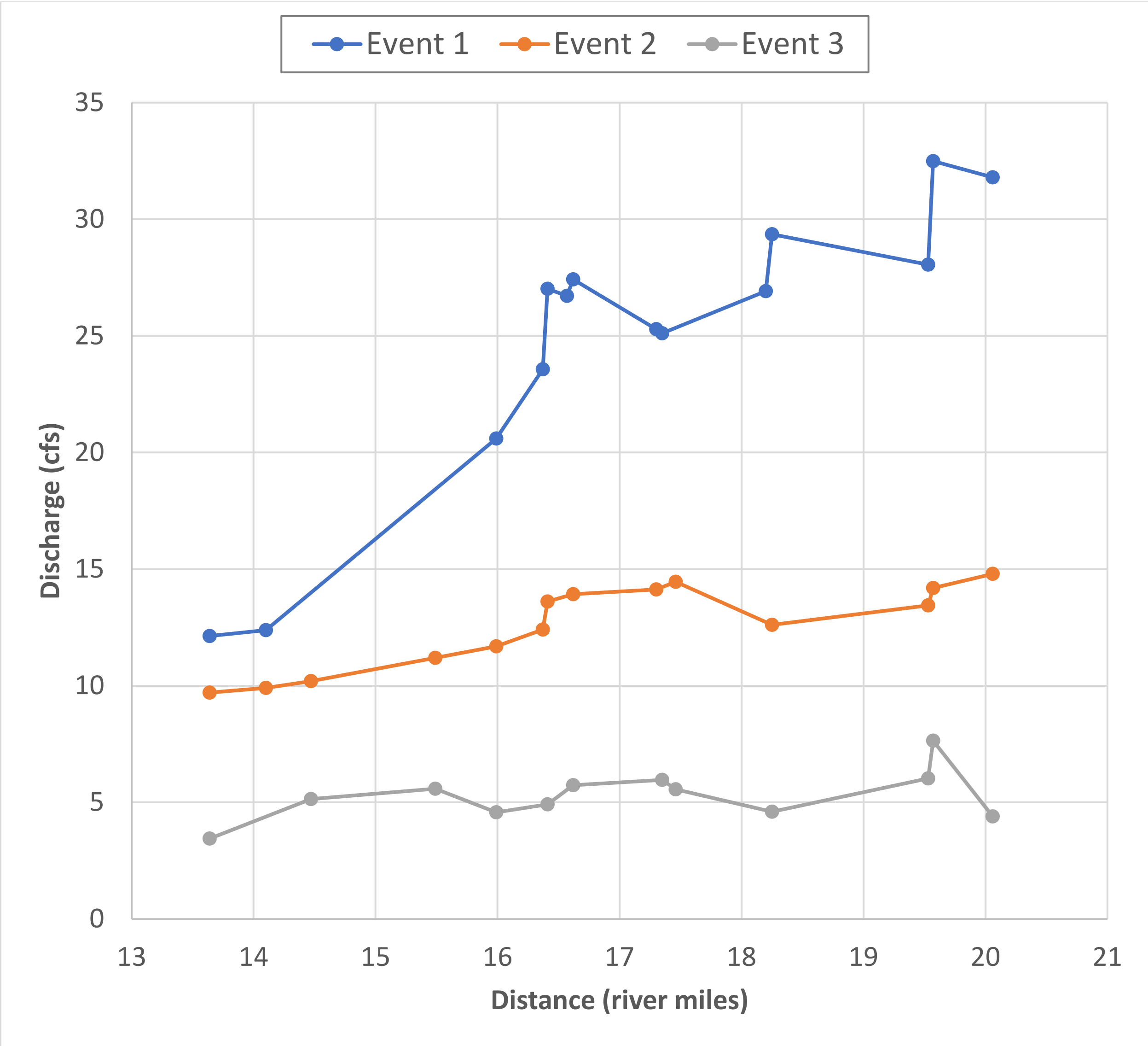

Figure 2: Gains and losses in discharge, measured in cubic feet per second (cfs) over distance (river miles) from Barton Creek headwaters. At each gauging event there were net gains across the ranch (includes tributary contributions) of 19.66 cfs, 5.09 cfs, and 0.95* cfs, respectively. Net gains across the ranch were calculated by subtracting the upstream flow measurement (South Fence) from the downstream flow measurement (East End).

*Data from Event 3 are flawed and are not an accurate representation of flow; these flaws are examined in the Discussion section.

Site Name	Location in River Miles	Flow in Cubic Feet per Second (cfs)					
		Event 1: June 20-21		Event 2: July 10-11		Event 3: July 22-24	
		Station Flow	Segment Gain/Loss	Station Flow	Segment Gain/Loss	Station Flow	Segment Gain/Loss
South Fence	13.64	12.13		9.71		3.45	
Griffin Tributary	14.1	0.25		0.2		--	
Kelsey	14.47	--		10.2	0.29	5.14	1.69
Nauman	15.49	--		11.2	1	5.58*	0.44*
Long Branch	15.99	20.6	8.22	11.69	0.49	4.58	-1*
Rocky US (calculated)	16.37	*23.57*	2.97	*12.41*	0.72	--	0.33*
Rocky Tributary	-	3.45		1.20		<0.1	
Rocky DS	16.41	27.02		13.61		4.91*	
Holman US	16.57	26.72	-0.3	--	--	--	0.83*
Holman Tributary	-	0.70		0.32		<0.1	
Holman DS	16.62	*27.42*		*13.93*		5.74*	
Chalk Knob US	17.3	25.29	-2.13	14.13	0.2	--	0.23
Chalk Knob DS	17.35	25.11		--		5.97*	
Horseshoe	17.46	--		14.46	0.33	5.56*	-0.41*
Abby US	18.2	26.91	1.8	--	-1.85	--	-0.96*
Abby DS	18.25	29.35		12.61		4.6	
White Branch US	19.53	28.05	-1.3	13.44	0.83	6.03	1.43
White Branch DS	19.57	32.49		14.19		7.64**	1.61
East End	20.06	31.79	-0.7	14.8	0.61	4.40**	-3.24
Percent of total flow gain from groundwater inputs along Main Stem Barton Creek:		**66%**		**88%**		**--**	
Percent of total flow gain from tributary contributions:		**34%**		**12%**		**--**	

Table 1: Flow measurements at each site during the three gauging events. Segment gains (green) or losses (red) are representative of the segment of Main Barton Creek upstream of the point on the table for which they are recorded.Sites not measured during the first event in June had not yet been selected. Kelsey, Nauman, and Horseshoe were added for Events 2 and 3 to provide greater detail. Italicized values were calculated from a tributary and corresponding main stem measurement. Sites not measured during Events 2 and 3 indicate tributaries that went dry or where discharge was too low to measure.

*These samples from Event 3 were collected following a rainfall event that increased flow in Barton Creek. These values cannot be compared to the other measurements collected during Event 3, thus any gains or losses based on these measurements are invalid and should be disregarded.

**The two most downstream sites were moved due to low flow conditions during the final gauging event and are not directly comparable to Events 1 and 2.

The upstream-most segment of Barton Creek from “South Fence” to the Rocky Creek confluence had the greatest and most consistent gains across the three events. Seep zones were observed, either visually or as temperature gradients presumed to be inflows at several locations on Barton Creek. Stark temperature gradients or cold inflows from channel alluvium were observed at the Long Branch confluence, Rocky Creek confluence, Holman Hollow, and downstream of the Abby confluence. Several discrete springs and seep zones were observed on the left bank of Barton Creek from Chalk Knob to Horseshoe (Photos 2-5). Horseshoe tributary was actually a short spring run created by several small seeps. Groundwater contributions along the main stem of Barton Creek were responsible for approximately 66% of total flow gain across Shield Ranch during Event 1 and 88% of total flow gain during Event 2.

Photo 2: Undercut Glen Rose outcrop with seep zone underneath overhang


Photo 3: One of several springs under overhanging Glen Rose outcrop


Photo 4: Spring along left bank of Barton Creek between Chalk Knob and Horseshoe

Photo 5: One discrete orifice of Horseshoe Springs

During Event 2, collaborators from BSEACD gauged flow at other Contributing Zone sites along Barton Creek both upstream and downstream of Shield Ranch. Significant flow gains are present throughout Barton Creek across the Contributing Zone (Figure 5). The detail across Shield Ranch illustrates the value of this type of flow measurement study.

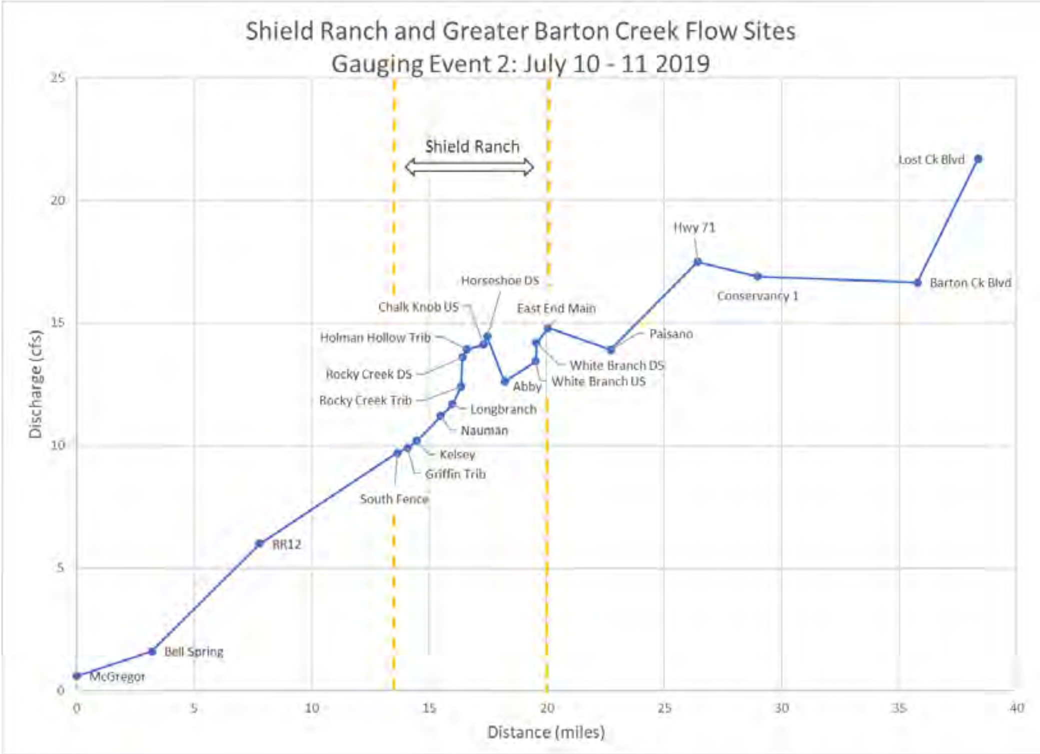

Figure 3: Flow measured during Gauging Event 2 on the upper 40 miles of Barton Creek. Shield Ranch extent shown in yellow.

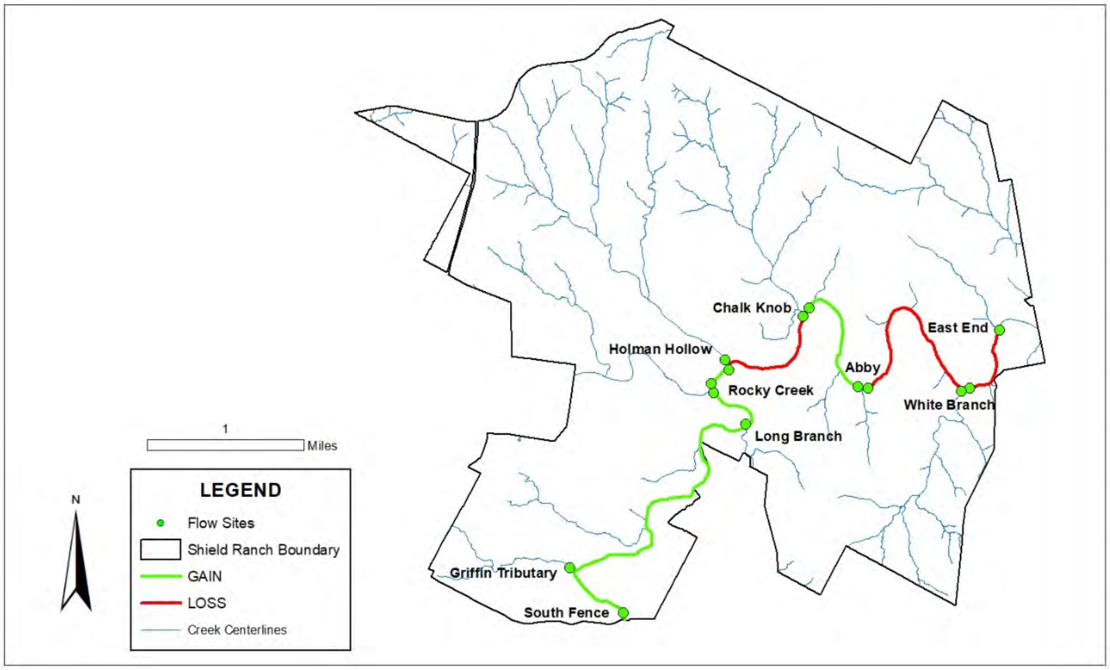

Figure 4: Gauging Event 1 Gains and Losses. Losses at the downstream end of the Ranch were very small (see Table 1), and all losses were within the QC margin of error for a measurement.

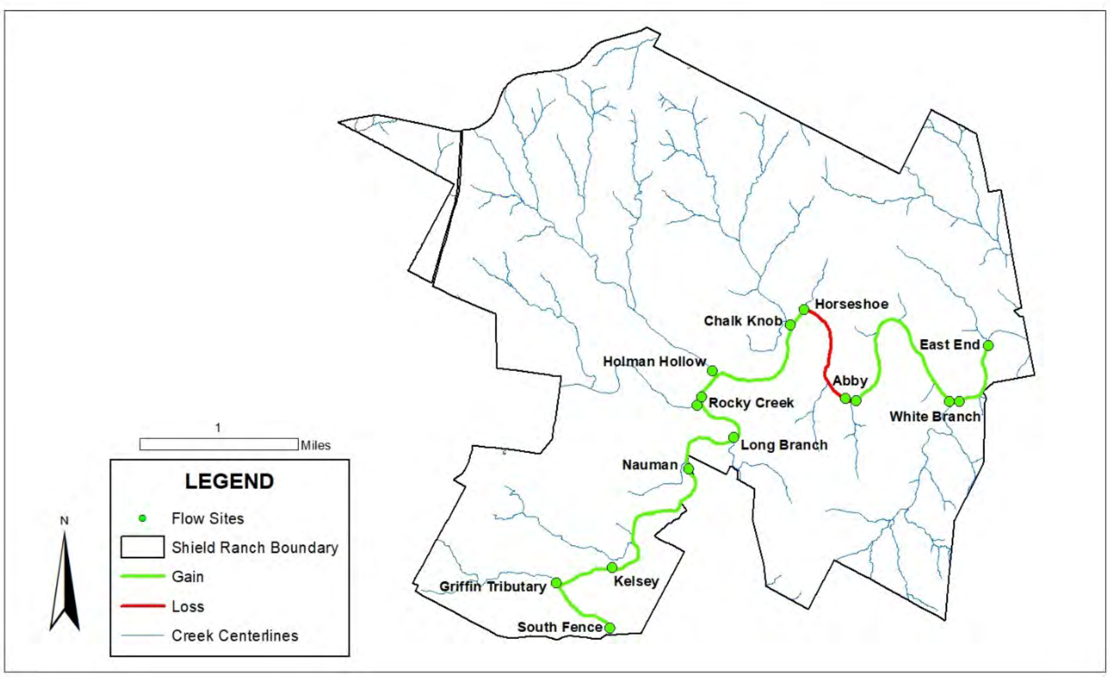

Figure 5: Gauging Event 2 Gains and Losses. The documented loss was relatively small.

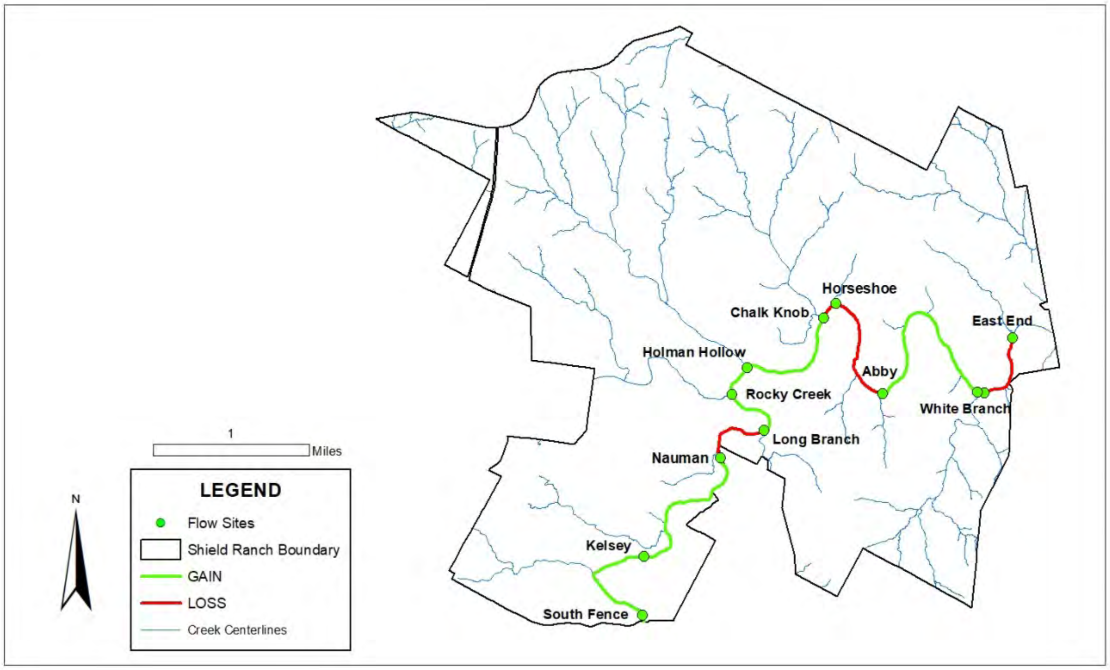

Figure 6: Gauging Event 3 (flawed) Gains and Losses. Low flows during this event made measurements difficult, and some stations were moved due to unsuitability. Additionally, a rainfall event that occurred in the middle of Event 3 rendered most of the measurements useless, including the ones that depict a loss between Nauman and Long Branch.

Figures 6-8 spatially represent the gaining and losing reaches within Shield Ranch during each of the gauging events. Main stem reaches upstream of Holman Hollow consistently showed flow gains (measurement from Event 3 is invalid). Reaches with flow losses were typically on the lower end of the ranch, and measurements frequently had to be taken at sites with alluvial channel bottoms where all flow may not have been detectable via ADV methods. Given that (1) a likely small, but unknown, percentage of flow could not be measured through the alluvium, and (2) the reaches with recorded losses were not consistent across the three gauging events, it is not possible to classify these small and inconsistent flow reductions as losses to karst features.

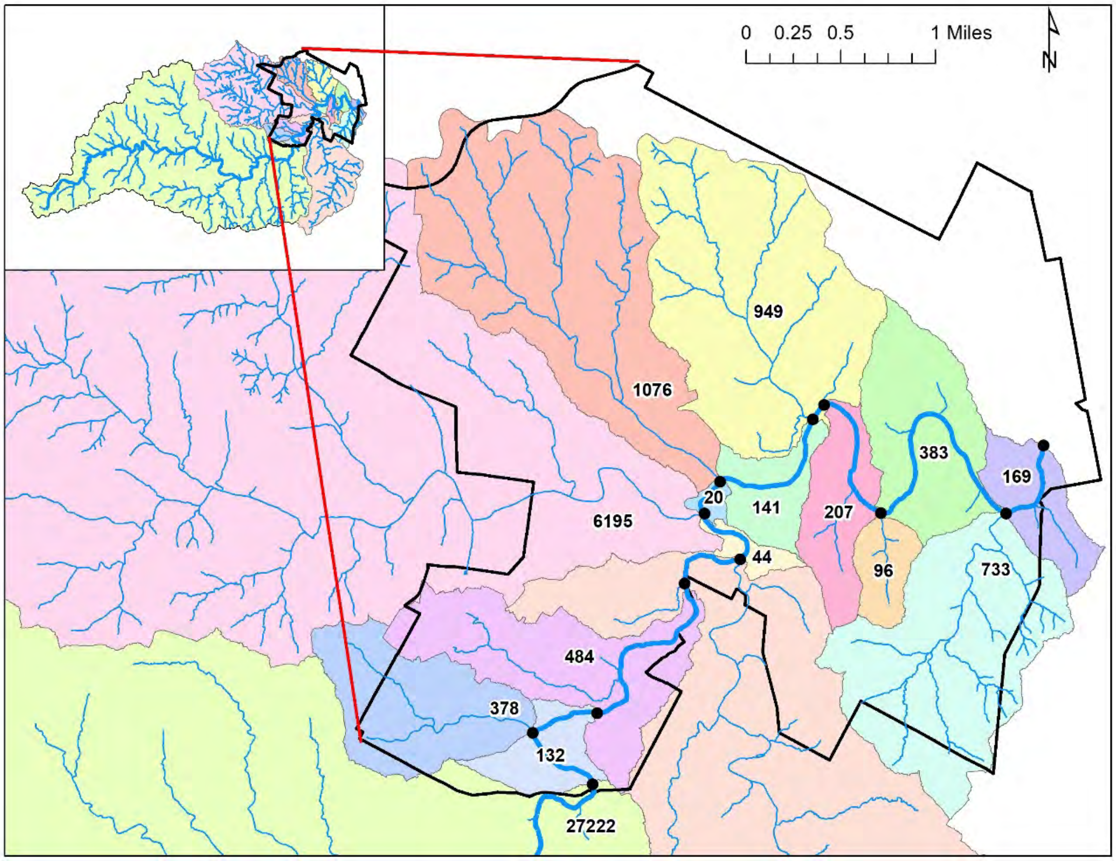

Figure 9: Drainage areas (in acres) to each flow site along Barton Creek within Shield Ranch. Several of these tributary watersheds are completely or nearly completely within the conservation easement boundaries. 37% of the study drainage area is protected by the Shield Ranch boundaries.

Figure 9 shows the areas of each subwatershed that drain to a gauging station along Barton Creek in this study. Percent of total flow gain in Events 1 and 2 versus corresponding subwatershed area is shown in Figure 10. A Pearson's product-moment correlation indicated a positive but statistically insignificant relationship between percent of total flow gain and drainage area (Event 1: ρ=0.56, P = 0.14; Event 2: ρ=0.47, P = 0.12), indicating flow gains are gravity-fed springs from the Trinity Aquifer rather than overland flow. Event 3 data were not considered.

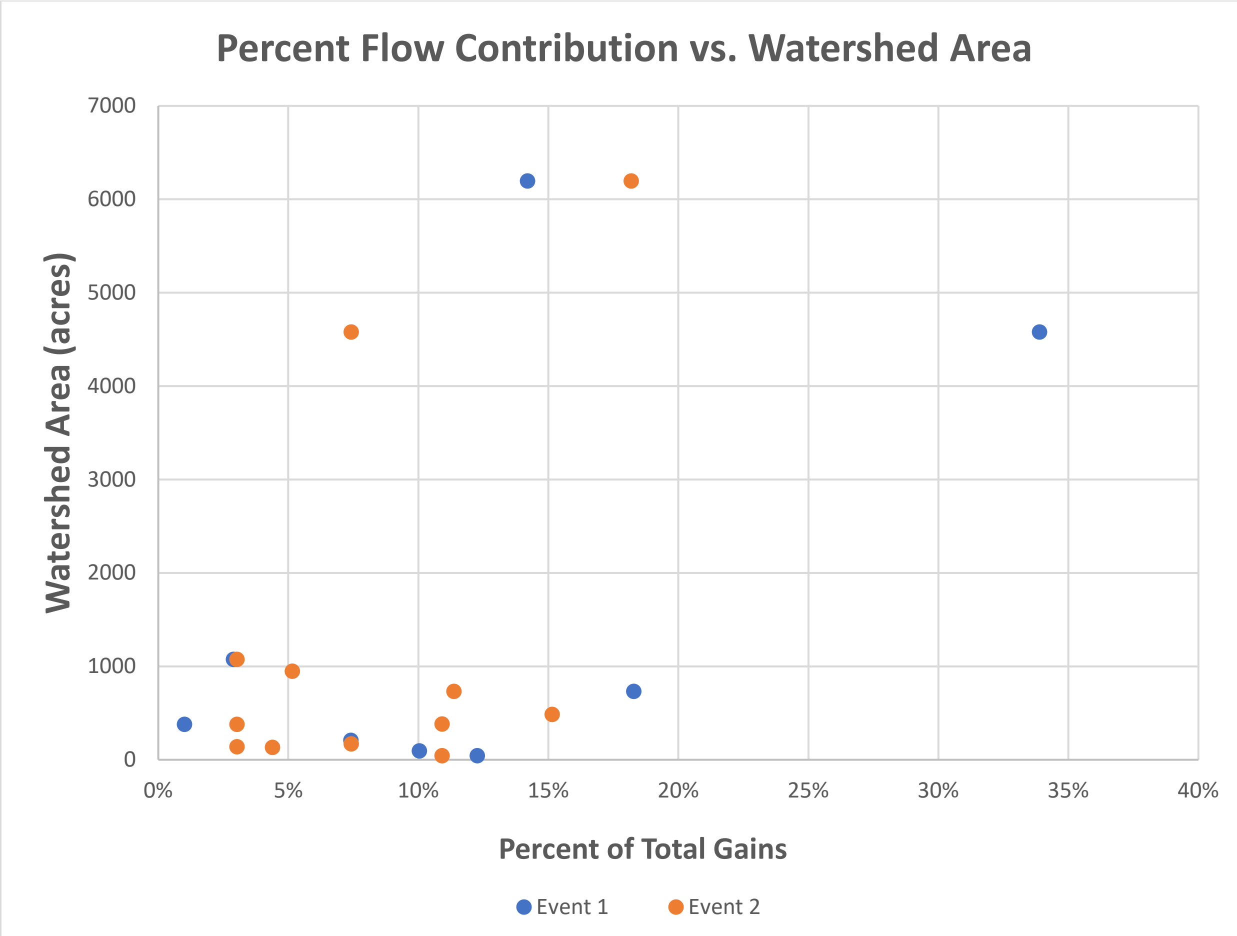

Figure 10: The percentage of flow gained by a segment was plotted against drainage area to help visualize any potential relationship between. Event 3 was not considered due to flaws discussed in the following section.

Discussion

Site Selection

Detailed flow measurements illustrate challenges in conducting this study as well as interpreting the results. Poor measurement cross sections, either due to water depth or channel bottom composition, made data interpretation most difficult during lower flows. While the ideal cross section for measuring flow at a site has a bedrock or less permeable channel bottom (Rantz et al., 1982), it was not always possible to select sites with those ideal conditions that also characterized the desired reaches and tributary inflows. Some stations selected were the best available option for quantifying a desired stream reach despite having alluvial channel bottoms. Three sites in particular stand out as problematic:

1. The location for measuring the main stem of Barton Creek downstream of the Long Branch confluence was not ideal due to its alluvial bottom, but was the best choice given very deep water immediately upstream and rapids immediately downstream. Long Branch surface flow contributions were impossible to quantify to a greater detail than

estimates due to channel morphology and flow conditions. The confluence with Barton Creek created a large backwater area that made measuring flow challenging in general and impossible using ADV methods on the upstream side. A significant temperature gradient suggested spring contributions in this same area as shown in Events 1 and 2.

2. The Abby tributary joins Barton Creek from the cut bank on river right, but at the time of the study there was a large gravel bar on the opposite bank. Water from Barton Creek could be observed moving through the gravel and cobbles of this deposit. The reach upstream of Abby was calculated as gaining during Event 1 but losing in Events 2 and 3. Rather than recharge to karst features, these “losses” likely indicate that, as creek levels dropped during the drying conditions, a greater proportion of creek discharge was flowing through the gravel bar and could not be measured. This is further supported by the presence of temperature gradients on both sides of Barton Creek near the Abby DS site, observed even after the tributary had gone dry, suggesting groundwater contributions rather than losses.

3. During Event 1, the Chalk Knob tributary was not flowing at the rate anticipated during the planning phase of this study, and the majority of visual flow contributions in the area were from springs along the bank of Barton Creek. Presumably due to inconsistencies in the cross sections of the upstream and downstream sites, Chalk Knob DS was measured as having a nominally lower flow (25.11 cfs) than Chalk Knob US (25.29 cfs) during the first event despite small visual inflows present between the two stations. This discrepancy is within the margin of error and not of great concern, but it does illustrate the inaccuracy that can be introduced by less-than-ideal site conditions. Given the similarity in measurements between the upstream and downstream sites during Event 1, only one of the two sites was measured during subsequent events.

Event 3 Problems and Invalid Data

There were several hurdles to gauging flow during Event 3. The information obtained from this sampling effort is useful in that it supports the coarse conclusion that Barton Creek remains a net gaining stream across Shield Ranch, even under the dry conditions of late summer with reduced spring contributions. However, inconsistencies because of low flow conditions, a minor storm event, and a longer sampling event duration render this data quality too poor to make conclusions about individual segment gains and losses within Shield Ranch.

Discharge in Barton Creek dropped by ~75% from the first event to the third event. Several tributaries were either dry or flow was too low to measure. This impacted data collection in two ways:

1. For all sites with alluvial channel bottoms during Event 3 (most sites), the proportion of flow that could not be detected by ADV methods was higher due to lower flow in the overall system, significantly increasing the inherent error at those sites (e.g. Abby tributary).

2. At some sites, the lower stream level and velocities made it impractical to collect a measurement, requiring the measurement be taken at a different location. For example,

both the East End site and the White Branch DS site were moved during Event 3 due to a high proportion of flow within alluvium rather than at the surface. This means the loss documented for the downstream-most segment is not representative of the same segment characterized in Events 1 and 2. Furthermore, the relocated White Branch DS site had a bedrock channel bottom, meaning nearly all the flow was likely captured by the Flowtracker. Conversely, the relocated East End site had a "solid alluvial bottom" as noted in the field notes, meaning some of the flow captured in the White Branch DS measurement was likely within the alluvium at the new East End site where it could not be detected. This "loss" is most likely more representative of site discrepancies than changes in flow.

Because of reduced staff availability, Event 3 took place over three days rather than the two days taken to collect measurements during Events 1 and 2. In addition to the inherent temporal variability an extra day introduces to the dataset, a small rainfall event occurred on the morning of the second day. Based on the small rise in Barton Creek discharge at Hwy 71 seen on Figure 3, this event increased flow and rendered the measurements collected on July 23rd essentially useless. The error this introduces is most obvious in the false "loss" between Nauman and Long Branch. Nauman was gauged the day of the storm under higher flow conditions while Long Branch was measured the following day when the minor stormflow had largely receded.

Rather than cancelling Event 3 following the rain event, sampling continued due to the impending conclusion of the WPD Internship Program and the opportunity for interns to observe how easily error can distort a dataset. While all data from Event 3 were presented in Table 1, the only conclusion that can reasonably be drawn from the flawed data is that even under much drier conditions than the first two events, Barton Creek remains a net gaining stream across Shield Ranch. We can safely make this determination because (1) the two most upstream sites and two most downstream sites were all measured on the first day of Event 3, making them temporally comparable; and (2) even at the relocated East End site, flow was >25% higher than at the upstream South Fence.

Spring Contributions and Measured Flow Loss

Overall, the results across all three gauging events demonstrate that Barton Creek is a primarily spring-fed, net gaining stream across Shield Ranch. Several springs and seep zones were observed either visually flowing directly into Barton Creek or detected as in-channel temperature gradients.

Groundwater contributions directly to the main stem of Barton Creek provided the majority of flow gains across the ranch in both Events 1 and 2, accounting for up to 66% and 88%, respectively, of inflows with tributaries providing the remainder of the contributions. These figures are likely biased slightly high given that flow in the Long Branch tributary had to be estimated visually due to challenging site conditions and may have been underestimated, but this discrepancy is likely small. The increase in the proportion of main-stem groundwater contributions between Events 1 and 2 is consistent with drying conditions and illustrates the effect of the drop in the water table: as higher elevation springs that feed tributaries went dry, lower elevation springs along the main stem continued to flow.

Furthermore, the positive but statistically insignificant relationship between subwatershed area and percentage of total flow gain during Events 1 and 2 is further evidence that Barton Creek under baseflow conditions is sourced primarily from gravity-fed springs within the unconfined, upper Trinity Aquifer. A stronger relationship between subwatershed area and percent total flow gain would be expected in a system where surface water inputs (e.g. tributary inflows) dominate flow contributions.

The flow losses measured in Barton Creek at Shield Ranch were minor, spatially and temporally inconsistent, and do not imply the presence of significant recharge features. This is in contrast to the substantial losses documented in upper Onion Creek, which indicated a connection to lower units of the Trinity Aquifer (Hunt et al., 2017). In stream segments with minor losses, some creek flow is likely moving downstream through the alluvium and not measurable by methods used in this study.

Conclusions & Implications

All three gauging events demonstrated that, overall, Barton Creek within Shield Ranch is a net-gaining stream. Trinity Aquifer springs are responsible for these gains in both the tributaries and the main stem of the creek. Over the summer, groundwater availability decreased as rainfall decreased over the Trinity Aquifer. As the system dried throughout the summer, declining spring inputs indicated that Trinity Aquifer springs are gravity fed and that the local water table drops seasonally.

The majority of gains were from groundwater contributions along the main stem of Barton Creek rather than tributary inflows. This proportion increased from Event 1 to Event 2 under lower flow conditions, illustrating the drop in the water table as higher elevation springs within tributaries had reduced discharge or went dry while lower elevation springs along the main stem continued to flow.

Losses were minimal and inconsistent both spatially and temporally, indicating shallow alluvial losses rather than the presence of significant recharge features attributable to geological formations.

As the climate continues to change, Central Texas is expected to become generally hotter and drier with precipitation falling in less frequent, more intense events (Nielsen-Gammon et al., 2021), exacerbating the seasonal drop in the water table. Furthermore, rapid population growth and urbanization in the area threaten both water quality and quantity. Preserving native landscapes maintains some of the natural resilience of the system and can help mitigate the impacts of climate change and urbanization to Central Texas streams and aquifers.

Acknowledgements

Special thank you to City of Austin Watershed Protection Internship Program, Shield Ranch, BSEACD, the rest of the Geologic Drainage Systems team (Scott Hiers, Radmon Rice, and David Johns), and many other Watershed staff for field assistance.

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