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Development Review

Differences in groundwater quality at springs influenced by effluent irrigation of golf courses in Austin, Texas.

Scott E. Hiers, P.G. and Chris Herrington

Water Resource Evaluation Section, Environmental Resource Management Division
Watershed Protection and Development Review Department, City of Austin
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Abstract

The use of recycled wastewater for golf course irrigation has become common practice as a means of achieving water conservation and avoiding discharge permit requirements. With increasing water shortage in arid and semiarid regions in western US, many communities are turning to reclaimed water as a water source. The benefits of recycled water are clear - conservation of potable drinking water by using reclaimed wastewater for irrigation of golf course and urban landscapes. However, potential problems exist in using recycled wastewater such as increasing the salinity in groundwater and soil and leaching of nutrients into water resources creating the need to study the long-term effects of using reclaimed wastewater on water resources. This study looks at differences in geochemistry at springs influenced by effluent irrigation from golf courses .The groundwater chemistry from five Austin area golf course springs were studied and compared to other springs in the Austin area as a measure of the relative impact of golf course irrigated by treated wastewater effluent on groundwater quality. Temporal trends in water chemistry data were also examined. Our results indicated that effluent-irrigated golf course springs yielded higher mean values than rural springs for 9 parameters including chloride, conductivity, fluoride, nickel, nitrate/nitrite and sulfate. However, springs associated with irrigation of urban landscapes had higher water chemistry concentration than springs influenced by golf courses using recycle wastewater for irrigation. In addition, temporal trends in water chemistry data were seen. Iron and nickel yield increasing temporal trends at some springs. Magnesium is the only ion which yields conflicting temporal trends between sites, exhibiting an increasing temporal trend at some springs and potentially but decreasing at other.

Introduction

The City of Austin has seen an increase in the number of golf courses since the mid-1990s. The impact of these golf courses to water quality of Austin's groundwater and surface water resources is a concern to City of Austin Watershed Protection & Development Review Department. The construction and turfgrass management of golf courses often requires the exposure of bare soil, fertilization, intensive irrigation, and use of pesticides. These practices could adversely affect the environment by increasing soil erosion, leaching nutrients and pesticides into water resources, and increase runoff concentration of sediment and applied chemicals. The intensive irrigation requirements of golf course turfgrass has resulted in golf course using reclaimed wastewater for their irrigation needs. Recycled wastewater is becoming a common water source for irrigating golf courses and urban landscapes, creating the need to study the effects of recycled water irrigation on water resources.

The effects of golf course construction and operation on surface water chemistry is well documented. In the Barton Creek Report, the City of Austin saw significant differences in surface water quality between land uses dominant land use golf courses when compared to other land uses (COA-ERM, 2007). The study concluded that nitrate nitrogen, ammonia, total dissolved solids, and total suspended solids concentration in surface water were significantly different compared to urban and residential uses. Similar findings in alkalinity, nitrogen, and cations were seen in between golf course managed area and unmanaged area in Canada (Winter and Dillion, 2005). In this study, we (1) examine the differences in groundwater chemistry from springs located near golf course irrigated with reclaimed wastewater and springs in urban and in rural areas; (2) and temporal changes in ground water chemistry over time.

Study Design

Five springs located on or adjacent to golf courses that are using recycled wastewater for irrigation were selected for the study (Table 1). Because of salt leaching, nutrient loading, and intense irrigation, we predict that ions, nutrients, alkalinity, and specific conductance should change over time and significant difference between golf course springs and rural springs. In addition, the median parameter concentrations should be significant different between springs with a golf course compare rural and urban land uses.

Table 1. Spring sites with short names used

Site #	Site Name	Short Name	Golf Course	Formation	Irrigation
104	Leif Johnson Spring	LJS	Barton Creek Properties	Glen Rose	Effluent
386	Great Hills Spring	GHS	Balcones Country Club	Trinity/Walnut	Mix of Trinity well water and effluent irrigation
662	Driving Range Spring	DRS	Jimmy Clay	Alluvial	Effluent
661	Roy Kizer Spring	RKS	Roy Kizer	Alluvial	Effluent
161	Lost Creek Spring A	LCS	Lost Creek Country Club	Glen Rose	Effluent

Spring sites were sampled twice annually beginning in 2002 and targeting the months of May and September. Samples were collected under non-storm influenced conditions. Some historical data collected prior to 2002 was considered for temporal trend analyses. Metals were only analyzed once annually at all sites.

Methods

Data were screened for outliers. All lead data on 18 October 2005 was removed from consideration because values at all sites were not consistent with any other measurements. Although sample dates and analysis methods are consistent during the study period (2002-2007), pre-existing historical data were derived using a variety of different analytical methods and with different frequencies at the study sites (Table 2).

Table 2. Summary of data available at study sites (number of samples, first year, last year).

PARAMETER	Leif Johnson (LJS)	Lost Creek A (LCS)	Great Hills (GHS)	Roy Kizer (RKS)	Driving Range (DRS)
Alkalinity (as CaCO3)	19 (1992-2006)	20 (1992-2006)	10 (1993-2006)	19 (1996-2006)	20 (1996-2006)
Ammonia-N	77 (1992-2006)	63 (1992-2006)	12 (1993-2006)	21 (1995-2006)	21 (1996-2006)
Arsenic	17 (1995-2006)	18 (1995-2006)	8 (1994-2006)	18 (1996-2006)	19 (1996-2006)
Calcium	19 (1992-2006)	20 (1992-2006)	9 (1993-2006)	18 (1996-2006)	19 (1996-2006)
Chloride	18 (1992-2006)	19 (1992-2006)	10 (1993-2006)	19 (1996-2006)	20 (1996-2006)
Conductivity	64 (1995-2006)	54 (1996-2006)	8 (1997-2006)	17 (1996-2006)	18 (1996-2006)
Copper	17 (1995-2006)	19 (1995-2006)	8 (1994-2006)	18 (1996-2006)	19 (1996-2006)
Dissolved Oxygen	17 (1996-2006)	8 (1996-2006)	7 (2002-2006)	9 (1996-2006)	9 (1996-2006)
E Coli Bacteria	4 (2004-2006)	3 (2005-2006)	5 (2004-2006)	5 (2004-2006)	5 (2004-2006)
Fecal Coliform	56 (1995-2003)	46 (1994-2003)	5 (1994-2003)	14 (1996-2003)	14 (1996-2003)
Flow	45 (1994-2005)	22 (1998-2005)	6 (2002-2006)	10 (1998-2005)	11 (1998-2005)
Fluoride	19 (1992-2006)	20 (1992-2006)	10 (1993-2006)	20 (1996-2006)	19 (1996-2006)
Iron	17 (1995-2006)	18 (1995-2006)	7 (1994-2006)	17 (1996-2006)	18 (1996-2006)
Lead	24 (1994-2006)	19 (1995-2006)	8 (1994-2006)	18 (1996-2006)	19 (1996-2006)
Magnesium	19 (1992-2006)	20 (1992-2006)	9 (1993-2006)	18 (1996-2006)	19 (1996-2006)
Nickel	16 (1995-2006)	18 (1996-2006)	8 (1994-2006)	18 (1996-2006)	19 (1996-2006)
Nitrate/Nitrite-N	52 (1992-2006)	49 (1992-2006)	10 (1993-2006)	19 (1996-2006)	19 (1996-2006)
Organic Carbon	24 (1994-2006)	19 (1995-2006)	10 (1993-2006)	19 (1996-2006)	20 (1996-2006)
Orthophosphorus-P	80 (1991-2006)	70 (1992-2006)	13 (1993-2006)	23 (1995-2006)	22 (1996-2006)
pH	80 (1990-2006)	63 (1990-2006)	10 (1994-2006)	19 (1995-2006)	19 (1996-2006)
Phosphorus-P	23 (1990-2003)	20 (1992-2002)	7 (1993-2003)	16 (1996-2003)	16 (1996-2003)
Potassium	18 (1995-2006)	19 (1995-2006)	9 (1993-2006)	18 (1996-2006)	19 (1996-2006)
Sodium	19 (1992-2006)	20 (1992-2006)	9 (1993-2006)	18 (1996-2006)	19 (1996-2006)
Sulfate	18 (1992-2006)	19 (1992-2006)	10 (1993-2006)	19 (1996-2006)	20 (1996-2006)
Total Kjeldahl Nitrogen-N	20 (1992-2003)	18 (1992-2002)	5 (1993-2003)	13 (1996-2003)	14 (1996-2003)
Turbidity	64 (1991-2006)	56 (1992-2006)	7 (1994-2006)	17 (1996-2006)	18 (1996-2006)
Water Temperature	55 (1990-2006)	54 (1990-2006)	10 (1994-2006)	18 (1995-2006)	18 (1996-2006)
Zinc	19 (1994-2006)	14 (1997-2006)	8 (1994-2006)	13 (1998-2006)	14 (1997-2006)

Differences between sites were analyzed by the non-parametric Kruskal-Wallis test in SAS using PROC NPAR1WAY and differences between individual sites explored by Ryan-Einot-Gabriel-Welsch multiple range test (SAS PROC GLM). A consistent date range (2002-present) was used for equivalent comparison and to limit analysis method inconsistencies. Sites were compared by non-parametric survival analysis methods using the STRATA statement in SAS PROC LIFETEST for datasets with censored observations (Allison 1995). Summary statistics for censored datasets calculated by Kaplan-Meier estimation methods.

Study sites were also compared to a rural undeveloped spring (Holman Hollow #372, Glen Rose formation), to a fully developed urban springs not impacted by effluent irrigation (Tubb Spring #504 and Stillhouse #24, both Edwards formation), and to springs in residential neighborhoods with effluent irrigation (Grotto Spring #577 and Barton Scenic Bluff #578 both Glen Rose formation) by methods identical to those used for assessment of site differences.

Temporal trends were assessed using least-square linear regression in SAS (SAS Institute, version 9.1) by PROC GLM. For datasets with censored values (i.e., less than detection limit), temporal trends were assessed by Cox proportional hazards regression (Allison 1995) using SAS PROC PHREG. All temporal trends were verified graphically. Temporal trends were assessed for both the period of record and only for the study period (2002-2007). Unless specified otherwise, a critical value (α) of 0.05 was used to determine statistical significance.

Results

A least-square linear regression analysis was completed in order to determine if any temporal trends were present in water chemistry data from five springs located near golf courses for both the period of record and during the study period (2002-2007). Few statistically significant trends are present (Table 3). No temporal trends are observed for any time period at any site for arsenic, copper, DO, *E coli* bacteria, flow, phosphorus, turbidity, and water temperature. Except for pH, iron, nickel, magnesium, and nitrate plus nitrite nitrogen few trends are significant both over the period of record and for data collected since 2002.

pH is increasing since 2002 at all sites except Lost Creek. Possible causes for this increase are the irrigation with high bicarbonate (>150mg/l) irrigation water and increases of carbon dioxide in soil and water from higher biological activity associated with root respiration of hybrid grasses and decay of organic material. Higher carbon oxide levels could result in an increase in dissolution of limestone. At high pH, above 7, the hydrolysis of calcite would create more OH^- resulting in pH increasing.

$$CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO^- + OH^-$$

Peacock and others reported increase in pH in soil and water, which they continued to irrigation of high bicarbonate water (Peacock and others, 1994). The lack of trend at Lost Creek since 2002 and the fact that pH concentrations are decreasing at Lost Creek and Leif Johnson spring for entire period of record requires closer examination of pH data. The pH data may be influenced by differences in electrode used to in measurement or sluggish and faulty electrodes, since before 2002 different field probes were used. The lack of trend in pH data at Lost Creek from 2002 to 2007 suggests that differences in turfgrass management practices such as the application sulfur containing fertilizers were improves phosphorus utilization and reduces the pH of alkaline and calcareous soils (USGA, 1994).

Iron and nickel yield increasing temporal trends at Lost Creek and Driving Range springs. The author suggests that the rise in iron may be indication of iron chlorosis. Excessive irrigation and soil compaction result in poorly aerated soils and reduced iron uptake. High phosphorus levels resulting from excessive fertilization and high levels of bicarbonate in irrigation water also interfere with iron uptake by plants (USGA, 1994).

Magnesium is the only ion which yields conflicting temporal trends between sites, exhibiting an increasing temporal trend at Great Hill Springs and potentially at Roy Kizer Springs but decreasing at Driving Range Springs. Driving Range and Roy Kizer springs yield similar decreasing temporal trends in ammonia, nitrate and conductivity with increasing temporal trends in fluoride. The conflicting temporal trend are indicative of complexities of evaluating water chemistry data and demonstrates the challenges of using recycle water and need of persistent

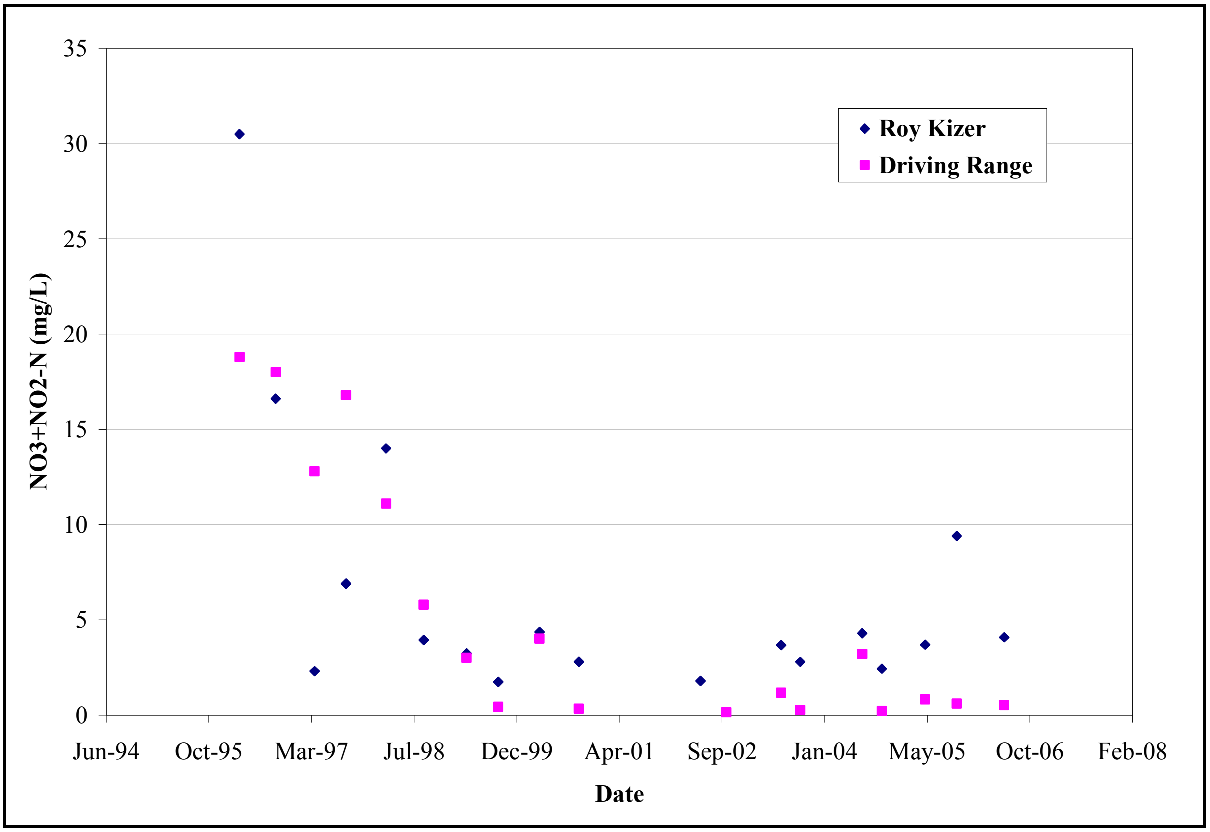
Table 3: Summary of temporal trends analysis results for all data and data collected since 2002.

PARAMETER	**DRS**		**GHS**		**LJS**		**LCS**		**RKS**	
	All	>2002	All	>2002	All	>2002	All	>2002	All	>2002
ALKALINITY (AS CACO3)	--	-	*	*	*	-	*	*	*	*
AMMONIA AS N	--	*	*	*	*	*	*	*	-	*
ARSENIC	*	*	*	*	*	*	*	*	*	*
CALCIUM	--	*	*	*	*	*	*	*	*	*
CHLORIDE	*	*	*	*	*	*	*	*	*	+
CONDUCTIVITY	--	*	*	*	--	*	*	*	-	*
COPPER	*	*	*	*	*	*	*	*	*	*
DISSOLVED OXYGEN	*	*	*	*	*	*	*	*	*	*
E COLI BACTERIA	*	*	*	*	*	*	*	*	*	*
FECAL COLIFORM BACTERIA	++	*	*	*	*	*	*	*	*	*
FLOW	*	*	*	*	*	*	*	*	*	*
FLUORIDE	++	++	*	*	*	*	*	*	++	*
IRON	+	*	*	*	*	*	+	*	*	*
LEAD	*	*	*	*	*	*	*	*	*	-
MAGNESIUM	--	*	++	*	*	*	*	*	*	+
NICKEL	++	*	*	*	*	*	++	*	*	*
NITRATE/NITRITE AS N	--	*	*	*	+	*	*	*	--	*
ORGANIC CARBON	*	*	+	+	*	+	*	*	*	++
ORTHOPHOSPHORUS AS P	*	*	*	*	*	*	--	*	*	*
PH	*	++	*	+	--	++	--	*	*	++
PHOSPHORUS AS P	*	*	*	*	*	*	*	*	*	*
POTASSIUM	*	*	++	*	++	*	*	*	*	*
SODIUM	*	*	++	*	*	*	*	*	*	++
SULFATE	--	*	*	*	*	*	*	*	*	*
TOTAL KJELDAHL NITROGEN AS N	*	*	*	*	*	*	--	*	*	*
TURBIDITY	*	*	*	*	*	*	*	*	*	*
WATER TEMPERATURE	*	*	*	*	*	*	*	*	*	*
ZINC	*	*	*	*	*	*	*	*	*	*

management and monitoring of water and soil conditions to reduce salt accumulation and manage nutrient, ion, and metal levels in soil and water. An example of successful manage of nutrients is seen in Roy Kiser data.

The decrease in nitrate and ammonia, figure 1, observed at the Roy Kizer Golf course is contributed to how the course was constructed. Originally, the golf course site was the location of wastewater treatment that was decommissioned in the early 1970's. The sludge pits still contained sludge with high nitrate and ammonia concentrations that was leaching into the shallow groundwater. During the construction of Roy Kizer course, the sludge material was stock piled and saved for the top dressing for the greens, the tee boxes and fairway areas so that the turf grass area could utilize the excess nutrients. The remediation effort worked, and nitrate and ammonia concentration decreased to significantly lower levels. The variations in turf grass management practices and golf course construction are factors that can effluence the water quality of water resources. The lack of consistent temporal trend in any single parameter and difference in parameter concentration between spring sites suggest that complex water-soil chemistry reactions in calcareous soils and variations in turf grass management practices and golf course construction are strong effluence on water chemistry at springs adjacent to golf course using recycled wastewater for irrigation.

Figure 1. Change in nitrate over time at Driving Range and Roy Kizer springs



Analysis of differences between golf course study sites, if present, may provide insight into the differential impacts of varying maintenance practices. Of the 28 parameters assessed, 11 yielded statistically significant differences between sites (Table 4). The 11 parameters are alkalinity, calcium, chloride, conductivity, fluoride, nickel, nitrate plus nitrogen-nitrogen, pH, potassium, sodium, and sulfate. Great Hills Springs yielded significantly higher concentrations of 9 other parameters than all other sites. These difference observed at Great Hill are possibly due to the fact that golf course sometime using groundwater from the Trinity Aquifer as makeup water. This groundwater has naturally higher in salinity. By mixing irrigation water with Trinity groundwater, one would expect the local groundwater to have elevated levels of conductivity and chloride concentration. However, the use Trinity groundwater would not account for the significantly higher bacteria levels. A piper diagram of bulk ion chemical composition also indicates that the Great Hill water is slightly dominant in Na + K/Chloride hydrogeochemical type water. This seen in grounding data more towards Na + K apex, and is within the sodium/potassium type hydrogeochemical classification with a slight chlorine dominant anion type. This is indicated by anion data plot more toward the chloride apex. The combined plotting of cation and anion data on diamond-shaped diagram shows that Great Hill spring data is plotting in upper right side. This suggests saline mixing with fresh water. The remaining sites are calcium/bicarbonate chemical composition.

Fluoride concentrations separate the sites into two distinct groups with lower concentrations observed at Lost Creek and Leif Johnson springs. Roy Kizer and Driving Range springs exhibit significantly lower magnesium concentrations than all other sites. The variability in these results, demonstrate the challenges of using recycle water and need of persistent management and monitoring of water and soil conditions to reduce salt accumulation and manage nutrient levels.

Golf course spring study sites were compared to other springs in the Austin area as a measure of the relative impact of golf course irrigated by treated wastewater effluent on groundwater quality (Table 5). Note that the higher mean value of arsenic at rural sites is based only on one detected value (6.43 µg/L, 23-JUL-2003).

Golf course springs were not different than rural spring for 17 of 28 parameters assessed including ammonia, copper, bacteria, lead, phosphorus and zinc (Table 6). However, effluent-irrigated golf course springs yielded higher mean values than rural springs for 9 parameters including chloride, conductivity, fluoride, nickel, nitrate/nitrite and sulfate. Golf course springs yielded higher fluoride concentrations than all other site groups. Golf course springs were greater than urban springs but not different than effluent-influenced urban springs for chloride, conductivity, sodium and sulfate. Nitrate/nitrite, magnesium, and alkalinity were higher at urban springs than golf course springs. There was no difference between urban springs or urban effluent-influenced springs and golf course springs for 18 of the 28 parameters assessed.

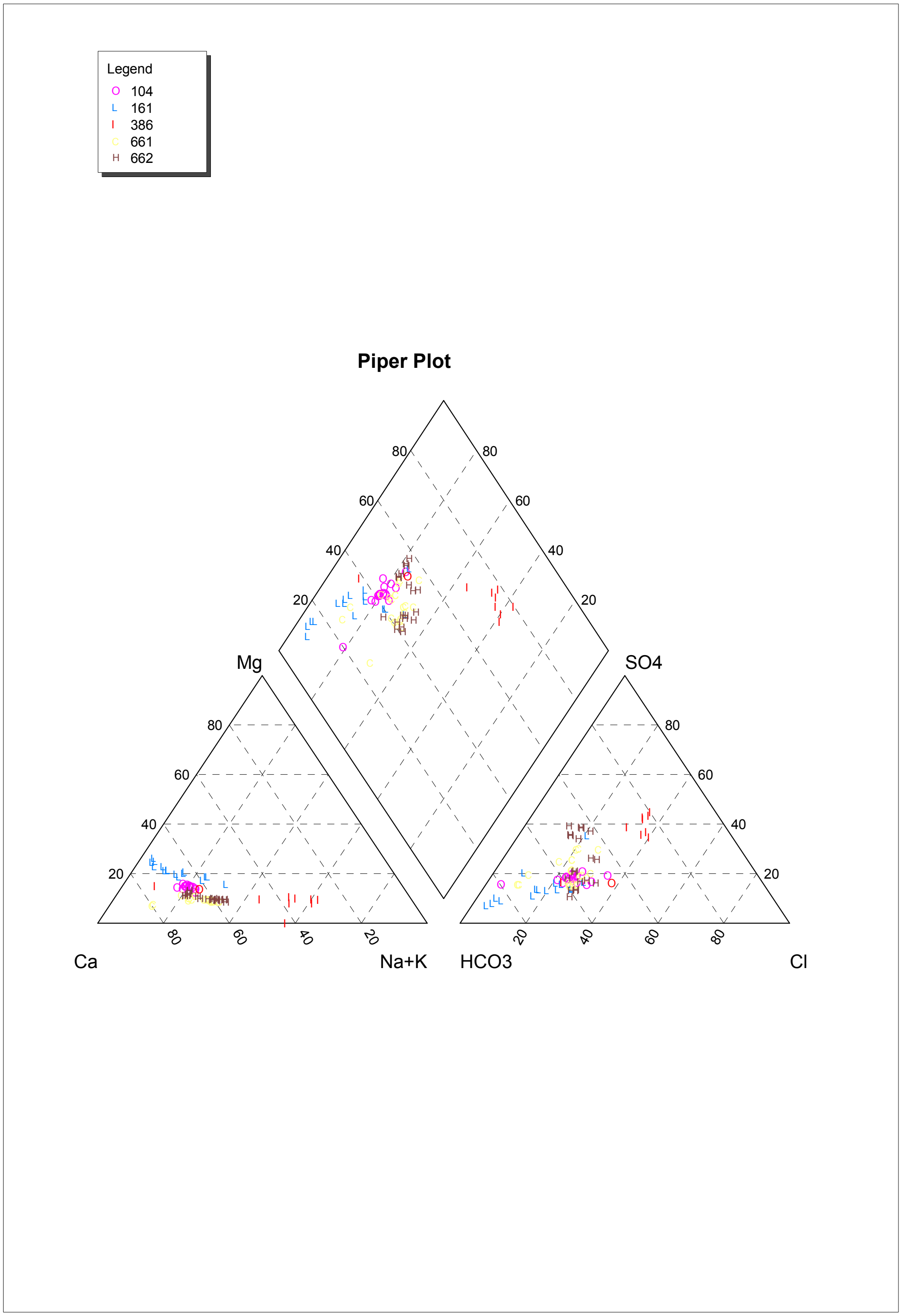
Golf course spring study sites were compared to other springs in the Austin area as a measure of the relative impact of golf course irrigated by treated wastewater effluent on groundwater quality (Table 5). Note that the higher mean value of arsenic at rural sites is based only on one detected value (6.43 µg/L, 23-JUL-2003).

Table 4: Summary of statistics and results of comparison test on differences between golf course sites.

PARAMETER	**UNIT**	**GHS**	**LJS**	**LCS**	**DRS**	**RKS**	**Sites Diff?**	**Notes**
Alkalinity	mg/L	323.429	301.000	321.000	289.125	325.375	Yes	
Ammonia-N	mg/L	0.008	0.009	*	0.007	*	No	
Arsenic	ug/L	1.845	1.281	1.992	1.686	2.230	No	
Calcium	mg/L	179.713	127.790	123.791	113.186	146.481	Yes	
Chloride	mg/L	301.714	67.450	57.667	81.513	88.025	Yes	GHS > all others
Conductivity	uS/cm	2471.429	909.000	869.857	885.375	1075.375	Yes	GHS > all others
Copper	ug/L	1.480	0.679	0.859	1.325	1.510	No	
DO	mg/L	7.471	5.688	4.157	5.993	5.128	Yes	GHS > all others
E Coli Bacteria	mpn/100mL	337.000	*	*	6.600	2.800	Yes	GHS > all others
Fecal Coliform	col/100mL	1288.500	8.000	108.667	152.667	38.000	No	
Flow	CFS	0.006	0.039	0.017	0.011	0.038	No	
Fluoride	mg/L	0.464	0.177	0.188	0.359	0.377	Yes	GHS,DRS,RKS>LCS,LJS
Iron	ug/L	189.620	19.745	28.400	34.267	102.200	No	
Lead	ug/L	9.590	15.337	17.388	12.986	21.900	No	
Magnesium	ug/L	30661.000	17794.000	23022.400	11277.857	12928.000	Yes	GHS > allDRS,RKS<all
Nickel	ug/L	4.153	2.023	5.522	7.066	7.009	Yes	
NO_3/NO_2-N	mg/L	3.524	1.901	3.145	0.868	4.020	Yes	
Organic Carbon	mg/L	3.970	1.596	2.030	2.551	2.469	Yes	GHS > all others
Orthop-P	mg/L	*	*	*	0.006	0.026	Yes	
pH	None	7.460	6.793	7.030	7.164	6.863	Yes	GHS > all others
Phosphorus-P	mg/L	*	0.020	*	*	0.060	No	
Potassium	mg/L	12.602	4.201	2.460	6.387	7.446	Yes	GHS > all others
Sodium	mg/L	351.441	40.371	35.926	67.401	67.124	Yes	GHS > all others
Sulfate	mg/L	495.143	70.988	51.950	67.650	94.550	Yes	GHS > all others
TKN-N	mg/L	0.240	0.270	0.110	0.270	0.280	No	
Turbidity	NTU	12.340	2.475	2.600	6.525	3.000	Yes	
Temperature	Deg C	19.949	20.476	19.754	22.514	20.930	Yes	
Zinc	ug/L	6.758	7.986	7.812	9.114	9.029	No	

*indicates all data less than detection limits.

Figure 2: Piper diagram of chemical compositions of spring water chemistry data.



ANOVA was used to determine significant differences between study springs originating in different geologic formations (Table 7). Trinity formation springs, represented only by the Great Hills Spring, yielded significantly higher concentrations of dissolved solids and ions than the springs in alluvial deposits or Glen Rose formation. Alluvial deposit springs were significantly higher than Glen Rose formation springs for several ions including chloride, fluoride, potassium and sodium and higher than all other springs for nickel and orthophosphorus.

Because Lost Creek and Leif Johnson springs occur in the Glen Rose formation as do the rural spring (Holman Hollow) and an urban effluent-irrigated spring (Scenic Bluff), these spring groups were directly compared so that natural differences between formations would be limited (Table 8). This provides a more direct comparison of the potential effects of effluent irrigation on golf courses. For the Glen Rose formation sites selected, effluent irrigation of golf courses may significantly increase concentrations of ions and nitrate above rural undeveloped concentrations but may not be significantly greater than concentrations observed at springs in developed residential areas with effluent irrigation. Concentrations of metals, however, do not appear to be different due to effluent irrigation.

Conclusions

The effects of golf course construction and operation on surface water chemistry is well documented. Numerous studies have demonstrated that if not closely managed, irrigation of reclaimed does impact surface water and groundwater resources. The results of our seven year study show that vary management practices can help reduce water quality impacts to waterbodies, but impacts will occur. A comparison of the mean concentrations for 28 water chemistry parameters show the golf courses springs site had high significantly higher concentration for 11 of 28 parameters monitored. Few statistically significant trends were observed and no one parameter showed a trend at all the monitoring sites. Variations in turfgrass management practices and complex water-soil chemistry reactions in calcareous soils may explain the lack of consistent temporal trend in any single parameter.

Several factor influence or temporal trend analysis and ANOVA were identified by analyzing for differences in water chemistry concentration between sites and completing piper diagrams analysis at the sites. The analysis of differences between golf course study sites help identifies the nitrate remediation at Roy Kizer and Jimmy Clay spring sites. Piper diagramming help identified the saline mixing of reclaimed wastewater with groundwater from Trinity aquifer. Once these factors were identified, a more direct comparison of the potential effects of effluent irrigation on golf courses was completed by accounting for natural differences between geologic formations and including addition landuse types. The result indicate that effluent irrigation of golf courses may significantly increase concentrations of ions and nitrate above rural undeveloped concentrations but may not be significantly greater than concentrations observed at springs in developed residential areas with effluent irrigation. This suggests that golf course which used reclaimed wastewater for irrigation might use better management practices utilizes using treated effluent for urban irrigation. Also, higher concentrations of metals appear to be sloe the result of treated effluent irrigation.

Table 5. Means by parameter (2002-2007) for the effluent-irrigated golf course springs (GC-EI), a rural spring (RURAL), urban springs (URBAN) and urban springs influenced by effluent irrigation (URB-EI).

Parameter	**Unit**	**GC-EI**	**RURAL**	**URBAN**	**URB-EI**
Alkalinity (as CaCO3)	mg/L	311.189	250.000	362.200	361.810
Ammonia-N	mg/L	0.008	0.036	0.013	0.012
Arsenic	ug/L	1.807	6.430	0.514	0.611
Calcium	mg/L	137.795	68.914	128.423	136.403
Chloride	mg/L	117.673	9.784	37.800	78.752
Conductivity	uS/cm	1219.658	487.857	963.175	1014.227
Copper	ug/L	1.088	*	1.030	0.761
Dissolved Oxygen	mg/L	5.681	4.670	7.336	5.542
E Coli Bacteria	mpn/100mL	79.364	3.000	35.667	46.667
Fecal Coliform	col/100mL	232.560	491.250	47.800	65.375
Flow	CFS	0.022	0.016	0.028	0.081
Fluoride	mg/L	0.315	0.243	0.196	0.209
Iron	ug/L	72.552	121.343	63.653	36.010
Lead	ug/L	12.708	11.960	3.841	12.241
Magnesium	ug/L	18533.656	21104.286	24198.571	24464.190
Nickel	ug/L	5.000	*	2.498	4.170
Nitrate/Nitrite-N	mg/L	2.645	0.030	5.841	3.523
Organic Carbon	mg/L	2.481	1.904	2.665	6.919
Orthophosphorus-P	mg/L	0.012	0.040	0.039	0.050
pH	None	7.052	7.326	7.266	6.942
Phosphorus-P	mg/L	0.023	0.020	0.039	0.020
Potassium	mg/L	6.692	0.874	31.344	3.131
Sodium	mg/L	109.767	4.794	20.744	52.172
Sulfate	mg/L	152.519	10.871	35.583	64.605
TKN-N	mg/L	0.178	0.247	0.197	0.181
Turbidity	NTU	4.886	4.000	4.528	2.218
Water Temperature	Deg C	20.771	20.389	20.446	21.394
Zinc	ug/L	7.885	11.643	3.660	4.996

Table 6. Summary of comparison testing between spring groups. Only significant differences noted.

Parameter	**Unit**	**GC-EI vs RURAL**	**GC-EI vs URBAN, URBAN-EI**
Alkalinity (as CaCO3)	mg/L	GC>Rural	U, UEI>GC
Ammonia-N	mg/L	no diff	no diff
Arsenic	ug/L	no diff	no diff
Calcium	mg/L	GC>Rural	no diff
Chloride	mg/L	GC>Rural	GC>U
Conductivity	uS/cm	GC>Rural	GC>U
Copper	ug/L	no diff	no diff
Dissolved Oxygen	mg/L	GC>Rural	U>GC,UEI
E Coli Bacteria	mpn/100mL	no diff	no diff
Fecal Coliform	col/100mL	no diff	no diff
Flow	CFS	no diff	no diff
Fluoride	**mg/L**	**GC>Rural**	**GC>all**
Iron	ug/L	no diff	no diff
Lead	ug/L	no diff	no diff
Magnesium	ug/L	no diff	U, UEI>GC
Nickel	ug/L	GC>Rural	no diff
Nitrate/Nitrite-N	mg/L	GC>Rural	U>GC,UEI
Organic Carbon	mg/L	no diff	no diff
Orthophosphorus-P	mg/L	no diff	no diff
pH	None	GC<Rural	no diff
Phosphorus-P	mg/L	no diff	U>GC,UEI
Potassium	mg/L	no diff	no diff
Sodium	mg/L	GC>Rural	GC>U
Sulfate	mg/L	GC>Rural	GC>U
TKN-N	mg/L	no diff	no diff
Turbidity	NTU	no diff	no diff
Water Temperature	Deg C	no diff	no diff
Zinc	ug/L	no diff	no diff

Table 7. Means of sites by formation with summary of ANOVA (Kruskal-Wallis test for non-censored datasets, LIFETEST for censored datasets) results.

Parameter	**Unit**	**Alluvial**	**Glen Rose**	**Trinity**	**ANOVA output**
Alkalinity (as CaCO3)	mg/L	307.250	309.571	323.429	no diff
Ammonia-N	mg/L	0.007	0.009	0.008	no diff
Arsenic	ug/L	1.958	1.637	1.845	no diff
Calcium	mg/L	129.833	126.124	179.713	Trinity>all others
Chloride	mg/L	84.769	63.257	301.714	Trinity>Alluvial>Glen Rose
Conductivity	uS/cm	980.375	890.733	2471.429	Trinity>all others
Copper	ug/L	1.348	0.770	1.480	no diff
Dissolved Oxygen	mg/L	5.560	4.973	7.471	Trinity>all others
E Coli Bacteria	mpn/100mL	4.700	*	337.000	Trinity>all others
Fecal Coliform	col/100mL	95.333	48.786	1288.500	no diff
Flow	CFS	0.025	0.030	0.006	no diff
Fluoride	mg/L	0.368	0.182	0.464	Trinity>Alluvial>Glen Rose
Iron	ug/L	67.967	22.465	189.620	Trinity>Glen Rose
Lead	ug/L	14.266	15.960	9.590	no diff
Magnesium	ug/L	12102.929	19972.500	30661.000	Trinity>Glen Rose>Alluvial
Nickel	ug/L	7.037	2.839	4.153	Alluvial>all others
Nitrate/Nitrite-N	mg/L	2.444	2.434	3.524	no diff
Organic Carbon	mg/L	2.470	1.755	3.970	Trinity>all others
Orthophosphorus-P	mg/L	0.019	*	*	Alluvial>all others
pH	None	7.013	6.903	7.460	Trinity>all others
Phosphorus-P	mg/L	0.060	0.020	*	no diff
Potassium	mg/L	6.917	3.476	12.602	Trinity>Alluvial>Glen Rose
Sodium	mg/L	67.263	38.519	351.441	Trinity>Alluvial>Glen Rose
Sulfate	mg/L	81.100	62.829	495.143	Trinity>all others
TKN-N	mg/L	0.272	0.142	0.240	no diff
Turbidity	NTU	4.763	2.533	12.340	Trinity>all others
Water Temperature	Deg C	21.722	20.139	19.949	no diff
Zinc	ug/L	9.044	7.918	6.758	no diff

*all values less than detection limit

Table 8. Means of site groups for Glen Rose formation springs with summary of ANOVA (Kruskal-Wallis test for non-censored datasets, LIFETEST for censored datasets) results.

Parameter	**Unit**	**GC-EI (LC,LJ)**	**RURAL (HH)**	**URB-EI (SBS)**	**ANOVA**
Alkalinity (as CaCO3)	mg/L	309.571	250.000	345.636	UEI>GC>Rural
Ammonia-N	mg/L	0.009	0.036	0.013	no diff
Arsenic	ug/L	1.637	6.430	6.560	no diff
Calcium	mg/L	126.124	68.914	122.146	GC,UEI>Rural
Chloride	mg/L	63.257	9.784	107.764	UEI>GC>Rural
Conductivity	uS/cm	890.733	487.857	1105.167	UEI>GC>Rural
Copper	ug/L	0.770	*	1.159	no diff
Dissolved Oxygen	mg/L	4.973	4.670	5.725	no diff
E Coli Bacteria	mpn/100mL	*	3.000	23.857	no diff
Fecal Coliform	col/100mL	48.786	491.250	4.250	no diff
Flow	CFS	0.030	0.016	0.133	no diff
Fluoride	mg/L	0.182	0.243	0.199	Rural>UEI,GC
Iron	ug/L	22.465	121.343	31.963	no diff
Lead	ug/L	15.960	11.960	11.913	no diff
Magnesium	ug/L	19972.500	21104.286	27085.545	UEI>Rural,GC
Nickel	ug/L	2.839	*	4.678	UEI>Rural
Nitrate/Nitrite-N	mg/L	2.434	0.033	3.104	UEI,GC>Rural
Organic Carbon	mg/L	1.755	1.819	2.666	no diff
Orthophosphorus-P	mg/L	*	0.040	0.050	no diff
pH	None	6.903	7.326	6.946	Rural>UEI,GC
Phosphorus-P	mg/L	0.020	0.020	0.020	no diff
Potassium	mg/L	3.476	0.874	3.323	GC,UEI>Rural
Sodium	mg/L	38.519	4.794	76.626	UEI>GC>Rural
Sulfate	mg/L	62.829	10.871	71.264	UEI,GC>Rural
TKN-N	mg/L	0.142	0.247	0.210	no diff
Turbidity	NTU	2.533	4.000	2.616	no diff
Water Temperature	Deg C	20.139	20.389	21.315	no diff
Zinc	ug/L	7.918	11.643	6.465	no diff

*all values less than detection limit

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