city of austin
Watershed Protection

Update of Barton Springs Water Quality Data Analysis - Austin, Texas

by Martha Turner, P.E., Engineer, Environmental Resources Management Division

ABSTRACT

*Barton Springs, the major discharge point for the Barton Springs segment of the Edwards Aquifer, is primary habitat for the endangered Barton Springs salamander (*Eurycea sosorum*), supplies a portion of Austin's drinking water, provides winter and drought baseflow to the Colorado River downstream, and is an important recreational resource. Significant time trends in Barton Springs have not been previously identified. However, the passage of time, continuing development, and increased data collection efforts combined with recognition of the importance of variable recharge/discharge conditions has led to additional data analysis. The current analysis of long-term water quality records (1975-1999) from Barton Springs indicates statistically significant changes in water quality potentially related to watershed urbanization. Increasing specific conductance, sulfate, turbidity, and total organic carbon trends were noted to be significant. A decreasing trend in dissolved oxygen concentrations was also significant in Barton Springs. Significant trends were not noted in other parameters that are commonly considered pollutants, such as nutrients and total suspended solids. However, when older, less verifiable data are included in the analysis, a long- term increase in nitrate nitrogen is statistically significant. Constraints associated with using this type of data analysis for future predictions are discussed.*

INTRODUCTION

COA staff (1997) and others (Barrett, 1996; TNRCC, 1995) have examined Barton Springs data at various times in the past for evidence that water quality is changing due to increasing urbanization in contributing watersheds and have not found any statistically significant time trends. With the continuing development in the contributing and recharge zone and additional data collection at Barton Springs, an update of the trend analysis was determined to be appropriate at this time. This analysis is also timely given the current effort to complete a Recovery Plan for the Barton Springs salamander. The focus of the current analysis was also expanded from investigating common non-point source pollution parameters (solids, nutrients, etc.) to all water chemistry parameters available for a significant period of record. Additional data treatment, including grouping by hydrological condition and removing questionable data influenced by short-term abnormal events, was performed to isolate long-term trends.

THE SPRING DATA

Treatment of Barton Springs water quality data requires an examination of the data source, storm conditions, recharge conditions, and impacts induced from short-term activities such as spills or pool maintenance.

Base Data Sources (COA and USGS)

Barton Springs data were extracted from the COA field sampling database. The COA Springs Project data, the USGS Barton Springs data, and the Austin-Travis County Health Department fecal coliform samples were selected. These are the largest and most comprehensive data sets available for Barton Springs, in both period of record and the number of parameters. These data are used in the analyses reported in this report. In addition, time series data collected with a Datasonde every 15 minutes for several years are presented, for one parameter, dissolved oxygen, to aid in interpretation of long-term data. Other available data sets not used in the analyses (TNRCC data, short-term COA sampling projects, citizen monitoring, etc.) are more sporadic in sampling frequency, do not meet quality control standards, and/or tend to be limited to just a few constituents.

Exclusion of Abnormal Conditions

Data reflecting two abnormal conditions, Barton Springs pool maintenance drawdown and a major sewer line failure, were removed before additional analysis was begun. Data from these events are not representative and could obscure trends in parameter levels caused by watershed impacts rather than localized short-term influences. This screening was conducted as a prudent evaluation of outlier conditions that were evaluated, documented, and removed before further analysis.

The rationale for excluding drawdown data is that they do not represent the normal discharge quality from Barton Springs. These data were originally obtained as part of a monitoring project to gauge the short-term effects of drawdown for maintenance cleaning on spring discharge quality. Typically, COA and USGS sampling is not conducted during pool drawdown. When Barton Springs pool is lowered, specific conductance and turbidity usually increase, and dissolved oxygen decreases (COA, 1997). Including these data would bias the analysis toward short-duration impacts rather than the capture of long-term trends. Therefore, drawdown sampling data from September 17, 1998 and September 18, 1998 events were not used.

In addition, dates where water quality is suspected to have been affected by documented sewer line breaks were removed from the data set (McReynolds, 1986; USGS, 1986). These sewer lines were repaired in April and November of 1982; however, neither the duration of the discharge nor the length of time necessary to flush the portion of the aquifer that was impacted can be determined. Plots were examined for high levels of ammonia (NH_3), total kjeldahl nitrogen (TKN), total suspended solids (TSS), and fecal coliform bacteria during baseflow to isolate the affected data. Concentrations greater than 0.06 mg/L NH_3, 0.5 mg/L TKN, 10 mg/L TSS, and 100 colonies/100ml fecal coliform during baseflow were considered indicative of the sewer line break impacts, based on examination of the entire data record. During 1981 and 1982 almost all baseflow concentrations were above these limits. Thus, all data from 1981 and 1982 were removed from the data set.

Hydrologic Condition Data Separation

The remaining data were then separated into three flow categories: baseflow without recharge, baseflow with recharge, and storm flow. This separation was performed because the factors affecting water quality in the springs differ under these three major flow conditions. During recharge, the water quality at the springs partially reflects the current water quality in the creeks, whether it is baseflow or storm flow (COA, 1997). Under baseflow without recharge, the spring discharge would primarily reflect the long-term changes in aquifer water quality.

Storm and baseflow:

Because neither rainfall in the large contributing area, nor flow in the recharging creeks, nor Barton Springs flow rate itself is a conclusive measure of the influence of stormflow conditions on the springs, discharge quality was used as a conservative separation indicator. If fecal coliform counts were greater than 100 colonies/100ml or TSS were greater than 10 mg/L, then the data were labeled as indicative of storm conditions. **If both fecal coliform counts and TSS concentrations were missing, the data from the sample were not used.** In addition, a concentration of intensive spring sampling had been done during three discrete periods when storm flow conditions were expected from the sampling design (personal communication: David Johns, COA). Data from these dates, 11/20/92-11/21/92, 5/30/96-6/1/96, and 9/11/98-9/14/98, were examined in detail, and if the pattern of increasing and decreasing fecal counts and TSS concentrations had a single peak, the data were split into storm and baseflow; otherwise, the data from these periods were labeled storm flow.

This partitioning of the data into flow categories is not precise because no definitive indicator exists of when the discharge from the springs should be considered storm flow. Rainfall histories throughout the contributing and recharge zone are not consistently available over the period of record. Flow paths vary with flow rate and have not been determined for the entire Barton Springs Recharge Zone through ongoing dye studies. Also, known travel times from the various recharge points range from 10 hours to 8 days, thus adding to the uncertainty. Traditional baseflow separation from gauging data was also not applicable in this case due to the flow and aquifer level variable recharge pathways and the desire to determine storm-influenced water-quality conditions rather than purely hydrologic storm flow conditions. In most cases, it was determined to be more appropriate to place the transition period of mixing storm and baseflow into the storm flow influenced category. In all cases, data placed in the wrong flow category will likely increase the variability in that category and obscure any actual trends occurring under either flow condition.

Recharge and non-recharge conditions

Daily flow in Barton Creek at Loop 360 was examined to determine if recharge was occurring. If the flow was greater than zero, then it was assumed that the data could be categorized as recharge. At times recharge may have been occurring from other watersheds when no flow was recorded at Barton Creek at Loop 360. However, as with the storm segregation, the absence of distributed rainfall records, uncertainties in transport through the aquifer, and data gaps in flow records make determination of recharge conditions problematic. From examination of the available flow records, separation based on the single continuous gage will be accurate in the vast majority of cases. Again, data placed in the wrong category will likely increase variability and obscure actual trends occurring in either recharge or non-recharge conditions. Additional analysis of flow data for other recharging creeks is ongoing.

DATA ANALYSIS METHODS

Trend Analysis – Multiple Regression

Multiple linear regression analysis was used to determine if parameter levels were changing over time, the direction of change, and the level of significance of the change. Regression analysis was performed for each parameter for three flow classes: baseflow with recharge, baseflow without recharge, and storm flow. A relationship between spring discharge levels and parameter levels for some parameters has been previously demonstrated at Barton Springs (Senger and Kreitler, 1984; COA, 1997). Therefore, spring discharge was entered first in the regression model, followed by time. Using this method, the variation due to time was distinguished from that due to spring discharge. Since turbidity had a large number of values at the detection limit, Cox regression was also used to confirm the results for this parameter. Cox regression is a semi-parametric method recommended for use with censored data (Allison, 1995). Significant relationships are identified as direct or inverse with time. For direct relationships, the variables increase together. For inverse relationships, as one variable increases, the other decreases. Relationships in which both the model and the date coefficient are significant at the 0.05 level are discussed. In addition, several relationships in which the model is significant at the 0.05 level but the date coefficient is only significant at the 0.10 level, were also identified, because more accurate storm and baseflow separation or the acquisition of more data may determine that a significant trend exists at the 0.05 level.

The results were then examined by plotting the data and looking for the trends determined analytically. The trends are not always visible and plots must be viewed with caution since statistically significant differences in Barton Springs discharge are present in different time periods and many of the parameters vary significantly with spring discharge under some flow conditions. In addition, the frequency pattern for all discharges does not match the frequency pattern for flow when samples were collected. Figure 1 illustrates changing flow patterns over time and the relationship between spring discharge and one parameter, dissolved oxygen (DO), under baseflow conditions. While DO concentrations vary with flow, the greater incidence of lower values through time at similar discharge levels results in a significant inverse relationship for DO that is not evident from the scatterplot.

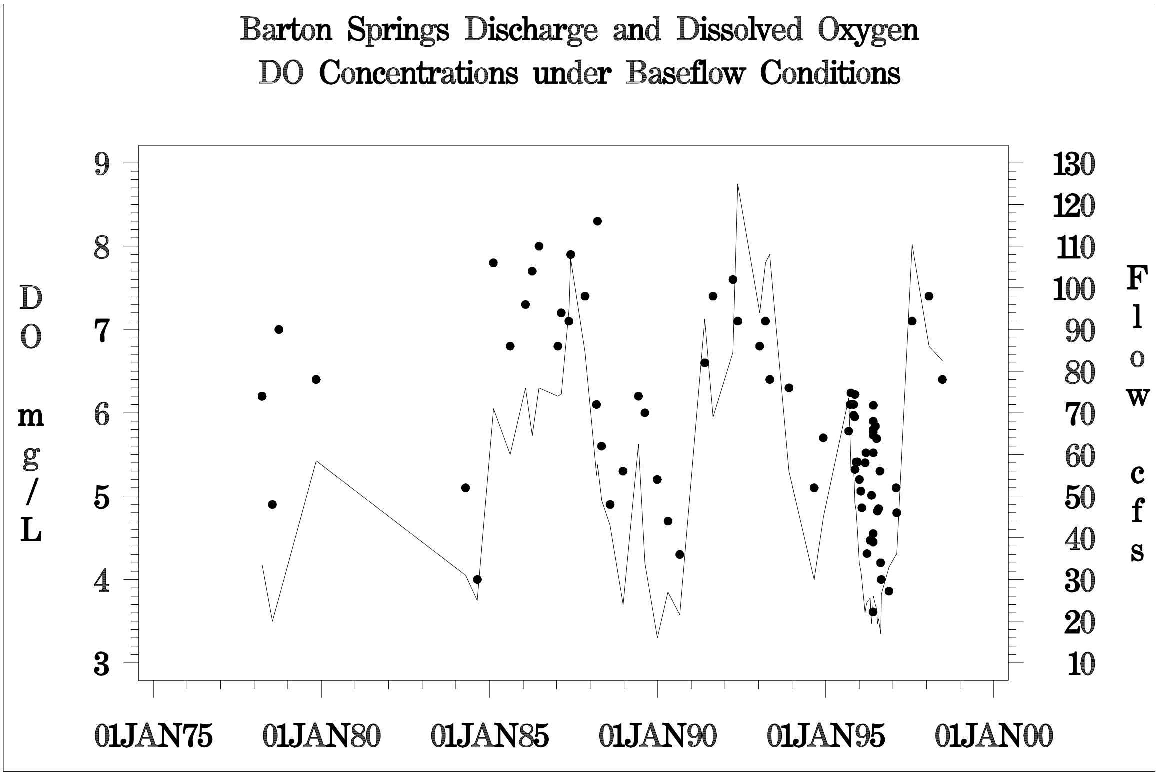
Magnitude of Change

In order to illustrate the magnitude of changes in constituent concentrations over time, three different methods were utilized. Normalized period medians were compared, the regression equation was used to predict the concentrations in 1980 and 2000, and the normalized period means with outliers removed were compared. The use of multiple methods in examination enhances the confidence in the results and was recommended by the Barton Springs Salamander Recovery Team. For all methods, the effect of changes in Barton Springs discharge was considered. When regression was used to predict the concentrations, the discharge was set to a rounded value of 50 cfs, near the long-term average for the discharge. For the means and medians, if the constituent had a significant relationship with spring discharge, the slope of the

regression equation was used to normalize the concentrations to those that would have been expected at an average discharge of 50 cfs. The equation used to normalize the data was:
Normalized concentration = original concentration + (regression coefficient for discharge)(50 cfs – spring discharge).*
Median concentrations were calculated for each 5-year period from 1975 to 1999 using the original data if the relationship with spring discharge was not significant, and the normalized data if it was significant. Medians were used rather than means to reduce the impact of outliers and values that are in the wrong category due to uncertainties in the data separation process. Five-year periods were selected as a common planning increment consistent with TNRCC evaluations of surface water bodies for evidence of water quality impairment in the Clean Water Act Section 303(d) assessments and NPDES permit actions.

Mean concentrations were calculated for each 5-year period from 1975 to 1999 using the original data if the relationship with spring discharge was not significant, and the normalized data if it was significant. Outliers were identified and removed prior to estimating the concentration means. Influence diagnostics[1] were used to identify individual values that overly affected parameter estimates from the regression. The earliest sampling dates are in either the 1975-1979 or the 1980-1984 period, depending on parameter. The increase or decrease in a parameter was determined by difference in the period medians from the earliest and most recent 5-year period. The percent change in the parameter concentrations was determined from the size of the change in the concentrations divided by the median concentration level during the earliest period.

Figure 1 Discharge (---) Compared With DO (.) Concentration Levels



---

[1] If the studentized residual was larger than 2 in absolute value, or if the DFFITS statistic was greater than the size adjusted cutoff of $2\sqrt{2/n}$, with n = number of observations, the data point was removed (SAS 1989).

RESULTS

Parameters with significant changes over time included conductivity, dissolved oxygen, organic carbon, sulfate, and turbidity. Regression r-squares, model and coefficient probabilities, and coefficient estimates and their standard errors are shown in Table 1. Numbers denoted with an asterisk (*) indicate regression coefficients for date (time trend) that were significant at the 0.10 level but not at the 0.05 alpha level. The multiple linear regression model using discharge followed by date was significant at the 0.05 level in all cases. The model r-square is not high in most cases, indicating that many factors, such as antecedent weather conditions, that affect the water quality of the spring discharge are not included in the model. These factors cannot be adequately characterized over the entire period from 1975 to 1999 and thus cannot be included in the model. Hence, the regression model should not be used to predict future water quality concentrations. In addition, it should be noted that the model is linear. Water-quality changes in response to environmental stresses may be linear over a certain range of stress levels and then change abruptly once a threshold is reached. However, a significant time coefficient in parameters of consequence to drinking water or aquatic life uses would demonstrate a trend for the worse in Barton Springs water quality.

Table 1
Regression R-Squares, Model and Coefficient Probabilities, and Coefficient Estimate

				Regression Coefficients					
		Model		**Discharge**			**Date**		
Parameter	**Flow Condition**	**Pr > F**	**R-Square**	**Pr > |t|**	**Coefficient Estimate**	**Std Error**	**Pr > |t|**	**Coefficient Estimate**	**Std Error**
Conductivity	Baseflow without Recharge	<0.0001	0.34	<0.0001	-1.19	0.14	0.0663	0.0037	0.002
	Baseflow with Recharge	0.0002	0.18	0.0304	-0.45	0.21	<0.0001	0.0106	0.0024
	Storm Flow	<0.0001	0.29	<0.0001	-0.98	0.14	0.0257	0.0051	0.0023
Dissolved Oxygen	Baseflow without Recharge	<0.0001	0.59	<0.0001	0.03	0.004	0.0016	-0.00015	0.00004
Organic Carbon	Storm Flow	0.0404	0.1	0.7538	0.01	0.03	0.0116	0.0009	0.0003
Sulfate	Baseflow with Recharge	0.0062	0.36	0.0163	-0.15	0.06	0.0016	0.0023	0.0006
Turbidity	Storm Flow	<0.0001	0.19	0.0001	-0.12	0.03	0.064	0.001	0.0005

Significant relationships to spring discharge are also listed in Table 1. In general, dissolved oxygen increases with increasing discharge, whereas conductivity, sulfate, and turbidity decrease with increasing discharge. Organic carbon is not significantly related to spring discharge under any flow condition.

The size, percent, and direction of the change in these five parameters with significant time trends are summarized in Table 2**.** Predictions of future conditions should not be made by extrapolating the rate of change during the past 20 years. Future rates of change will depend on the rates of change in environmental stress and possible threshold conditions. The paragraphs below describe the significant changes identified for each individual parameter by this analysis

Conductivity

Conductivity has increased during all flow conditions over the past 20 to 25 years. The largest change is observed during baseflow with recharge and is estimated to be less than a 15% change. Storm flow changes are estimated to be less than 7%, and during baseflow without recharge, the change is less than 5%. The median concentration estimate during baseflow without recharge increased from 655 to 677 uS/cm. For comparison, these concentrations both lie between the mean baseflow concentrations of 566 for much smaller rural springs and 867 uS/cm for much smaller newer urban springs, respectively, in the Jollyville Plateau (COA, 1999). However, the increase noted in Barton Springs may be an indicator of future change in Barton Springs to more of an urban signature. Scatterplots of these data are provided in Figures 2 through 5.

Dissolved Oxygen (DO)

Scatterplots of DO data are provided in Figures 6 through 9. DO has decreased over time during baseflow, when recharge was not occurring. During non-recharge, at low spring discharge levels, the measured DO sometimes drops below 4 mg/L. DO is significantly directly related to spring discharge levels, but DO is decreasing both at high discharge levels and at low ones. The median dissolved oxygen concentration has decreased approximately 1.1 mg/L over the last 25 years, from 6.8 to 5.7 mg/L. This is a decrease of 16%. Sampling has been much more frequent recently, leading to a higher probability of observing extreme events. Therefore it is possible that the change is a sampling artifact. However, DO concentrations in Barton Springs, tracked with a Datasonde (data at 6-hour intervals over month-long periods) have been below 4 mg/L 11% of the time during an approximately 4-year period of record as indicated in Figure 9. The plots of the Datasonde data, which were not included in the regression or magnitude of change calculations, compared with the discrete DO data show that low DO levels may predominate during periods without much recharge. The Datasonde data has yet to be scrutinized carefully for drift or calibration problems, but it does indicate the potential for the occurrence of low DO in the springs. Naturally a long-term change in DO of greater than 1 mg/L is significant in any isolated aquatic habitat.

Table 2
Magnitude and Percent Change in Constituent Levels Over 20 to 25 Years

		Normalized Period Medians				Predicted from Regression at 50 cfs				Normalized Period Means with outliers removed			
Parameter	**Flow Condition**	**1975-1979 or 1980-1984^ Median**	**1995-1999 Median**	**Change over approx. 20 years**	**Percent Change**	**Prediction 1-1-1980**	**Prediction 1-1-2000**	**Change over 20 years**	**Percent Change**	**1975-1979 or 1980-1984^ Mean**	**1995-1999 Mean**	**Change over approx. 20 years**	**Percent Change**
Conductivity (uS/cm)	Baseflow without Recharge	655	677	22	3%	642	668	27	4%	651	658	7	1.1%
	Baseflow with Recharge	590^	646	56	9%	574	651	78	14%	569^	645	76	13.0%
	Storm Flow	624	642	18	3%	601	638	37	6%	624	640	16	2.6%
Dissolved Oxygen (mg/L)	Baseflow without Recharge	6.8	5.7	-1.1	-16%	6.5	5.45	-1.1	-16%	6.4	5.6	-0.8	-12.5%
Organic Carbon (mg/L)	Storm Flow	1.5	3.4	1.9	127%	-0.68	5.8	6.5	799%	1.5	4.2	2.7	180.0%
Sulfate (mg/L)	Baseflow with Recharge	28.3^	38.8	10.5	37%	25.1	41.7	16.6	66%	28.3 ^	37.6	9.3	33.0%
Turbidity (NTU)	Storm Flow	5.3	7	1.7*	32%*	3.7	11.2	7.5*	203%*	5.3	7.3	2*	37.7%*

* significant at the 0.1 level but not at the 0.05 level

^ actually 1980, 1983, and 1984 since 1981 and 1982 were removed from the analysis due to a sewer line break

Figure 2 Conductivity During Baseflow Without Recharge

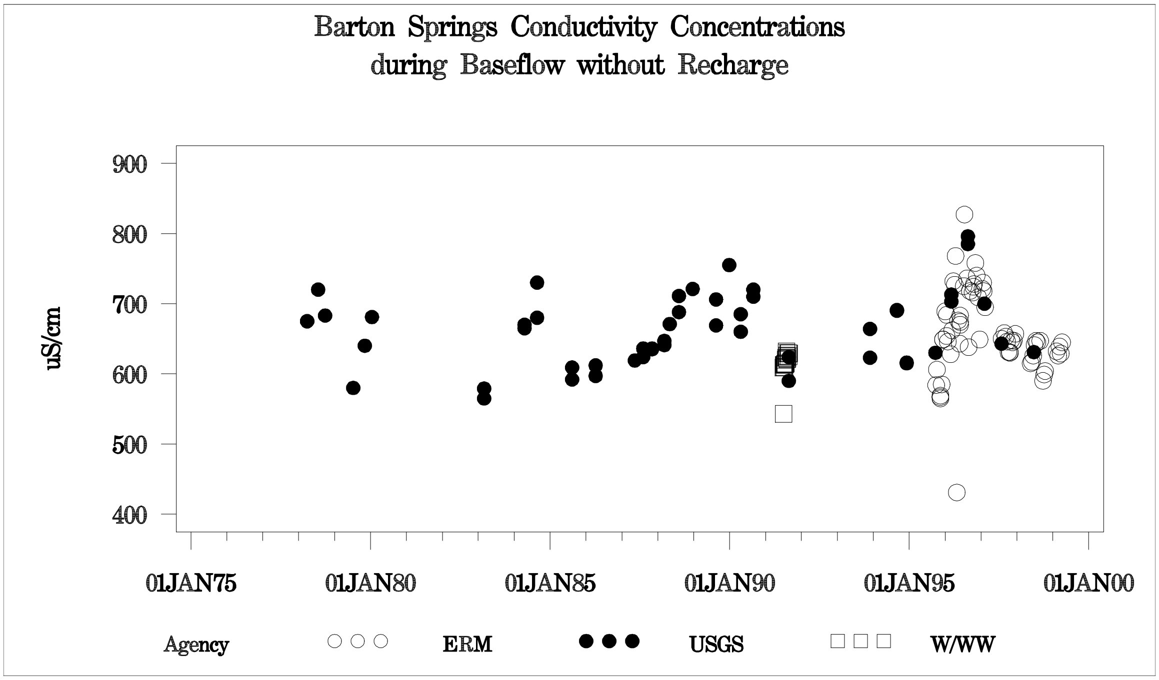


Figure 3 Conductivity During Baseflow With Recharge

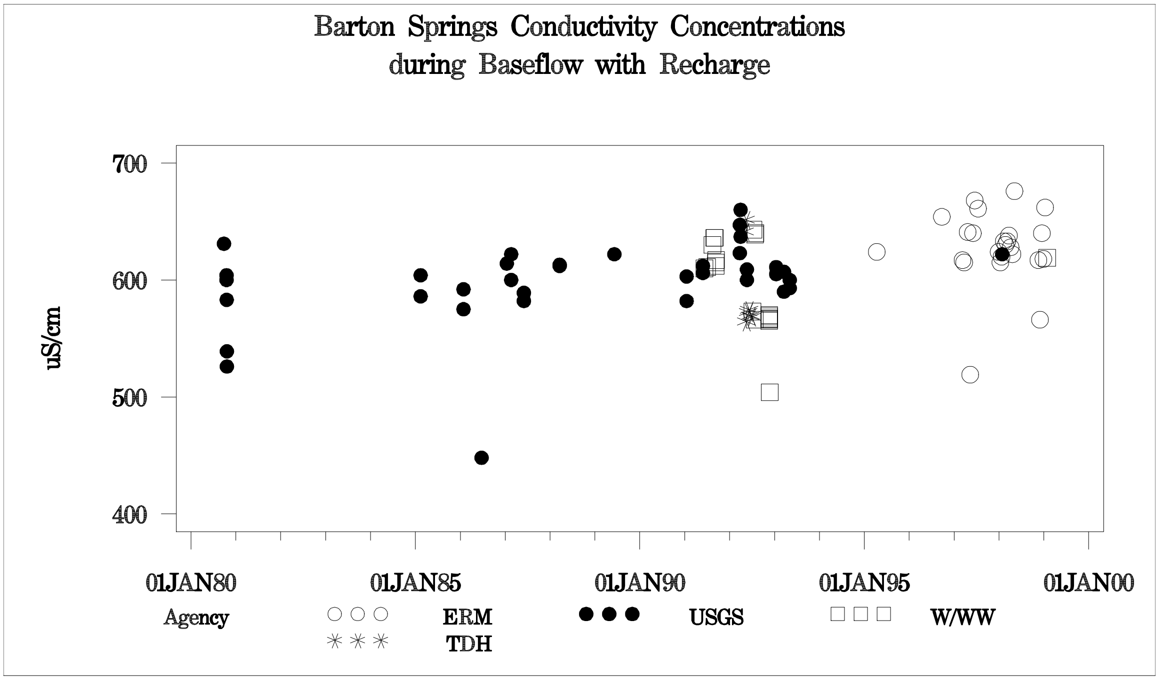


Figure 4 Conductivity During Storm Flow

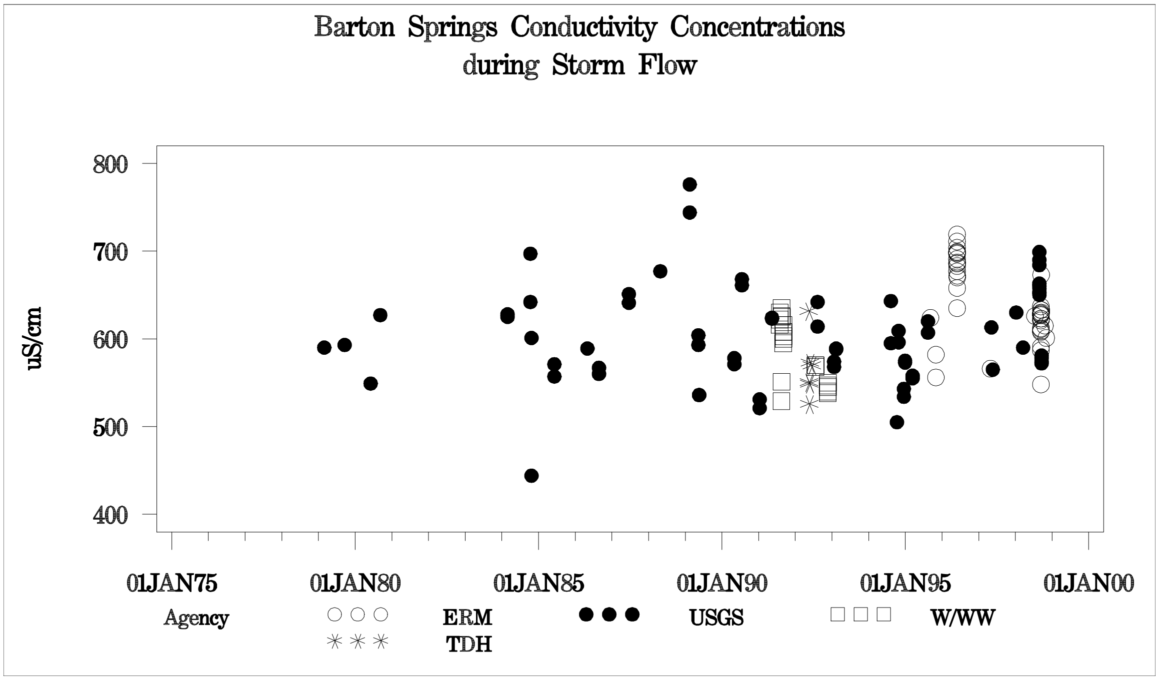


Figure 5 Normalized Conductivity During Storm Flow

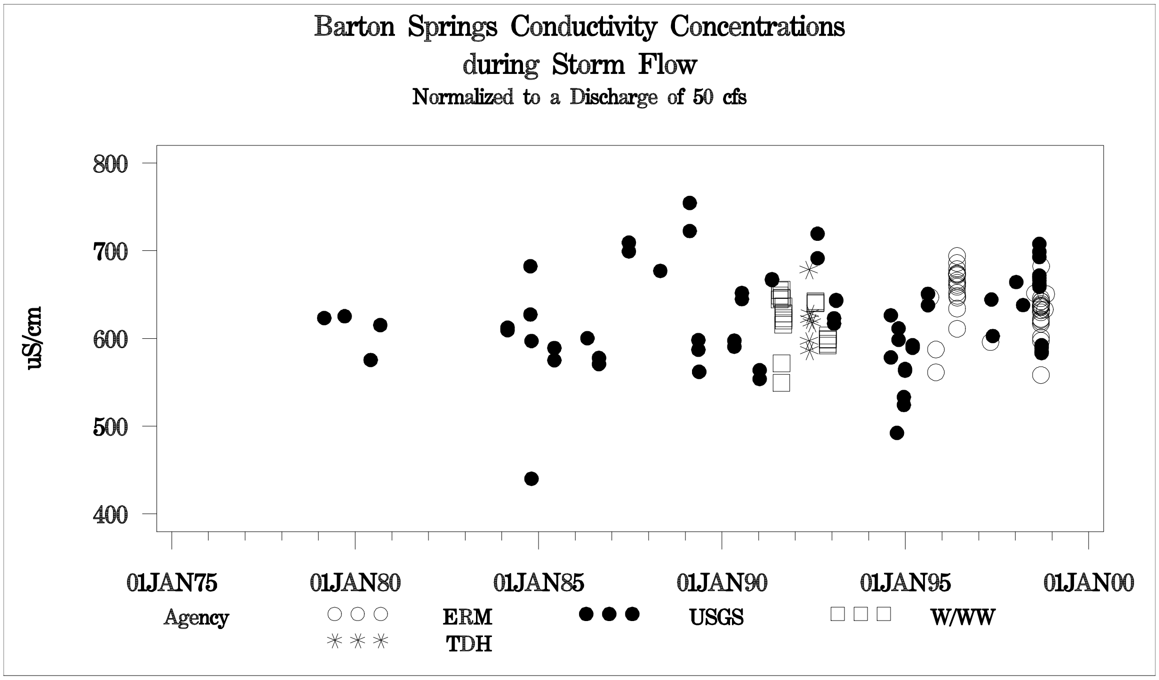


Figure 6 Dissolved Oxygen During Baseflow Without Recharge

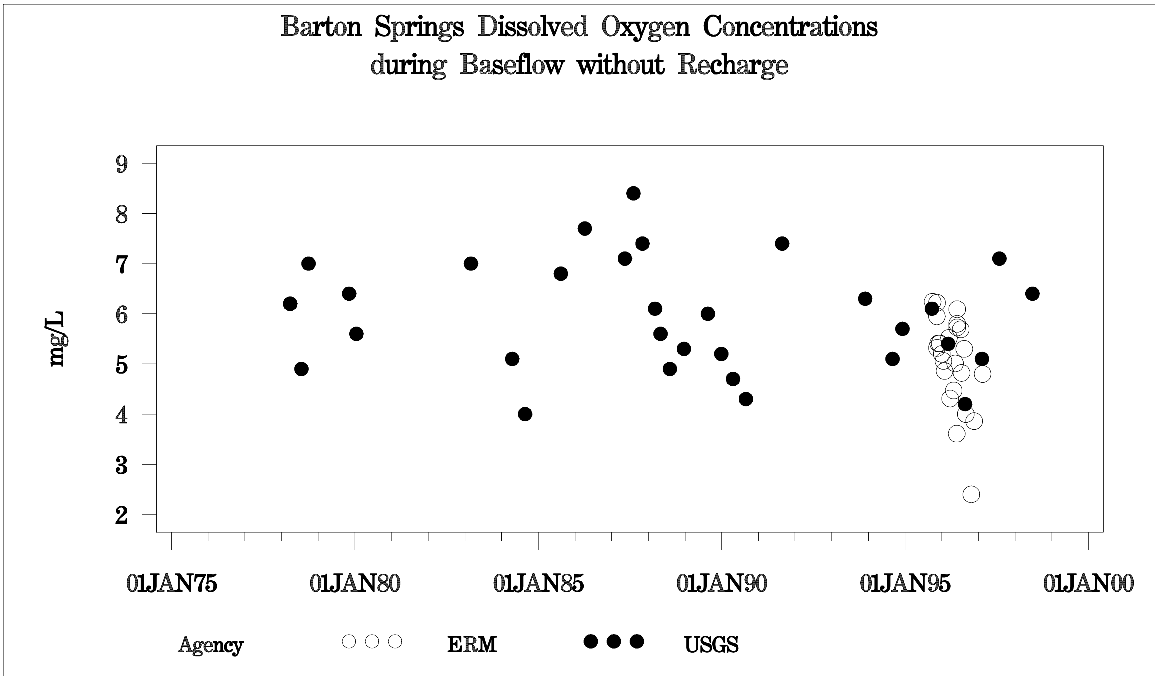


Figure 7 Normalized Dissolved Oxygen During Baseflow Without Recharge

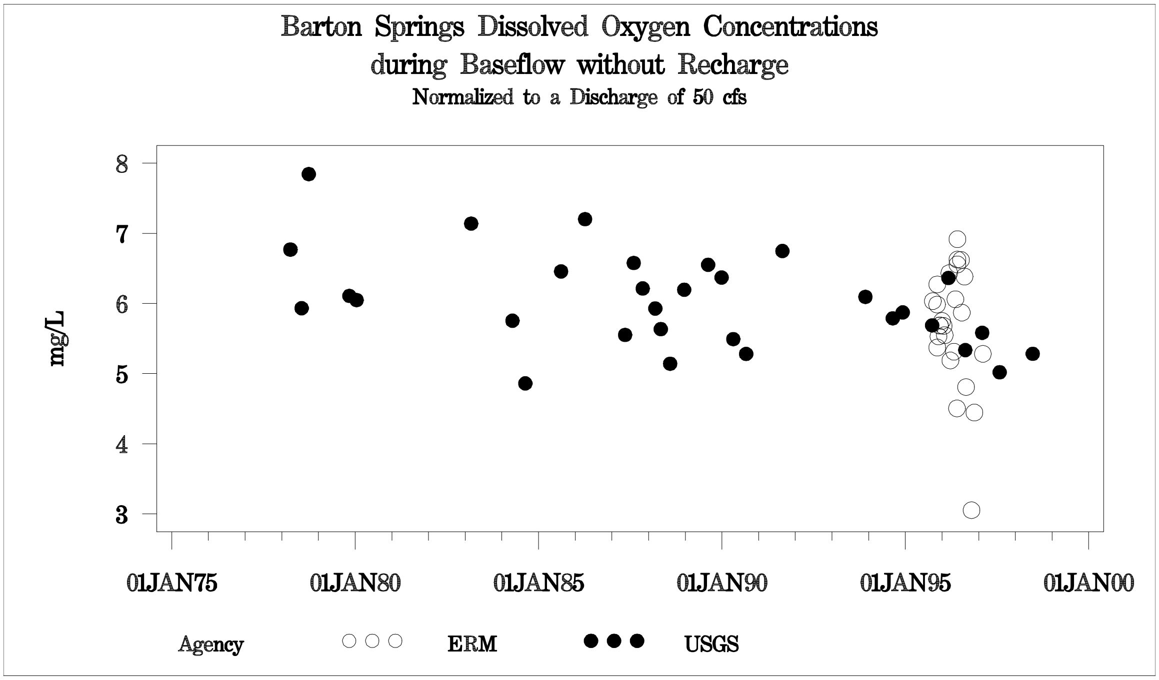


Figure 8 Datasonde Dissolved Oxygen in Barton Springs

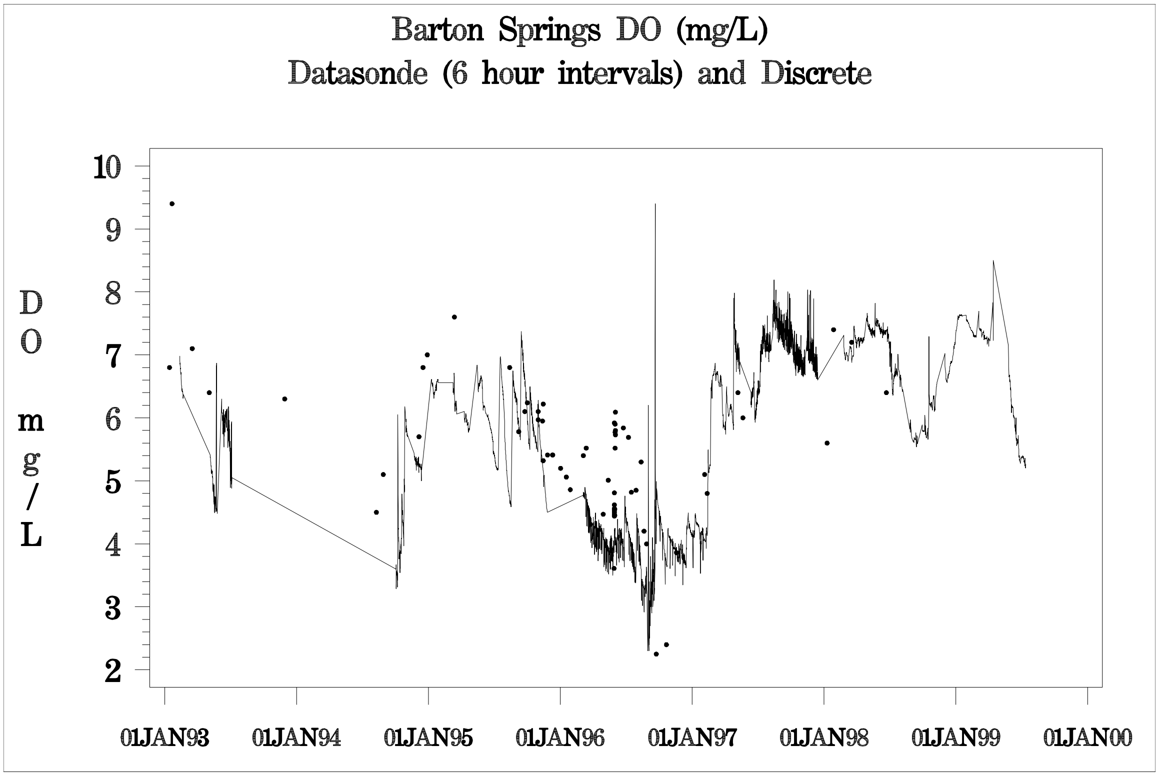
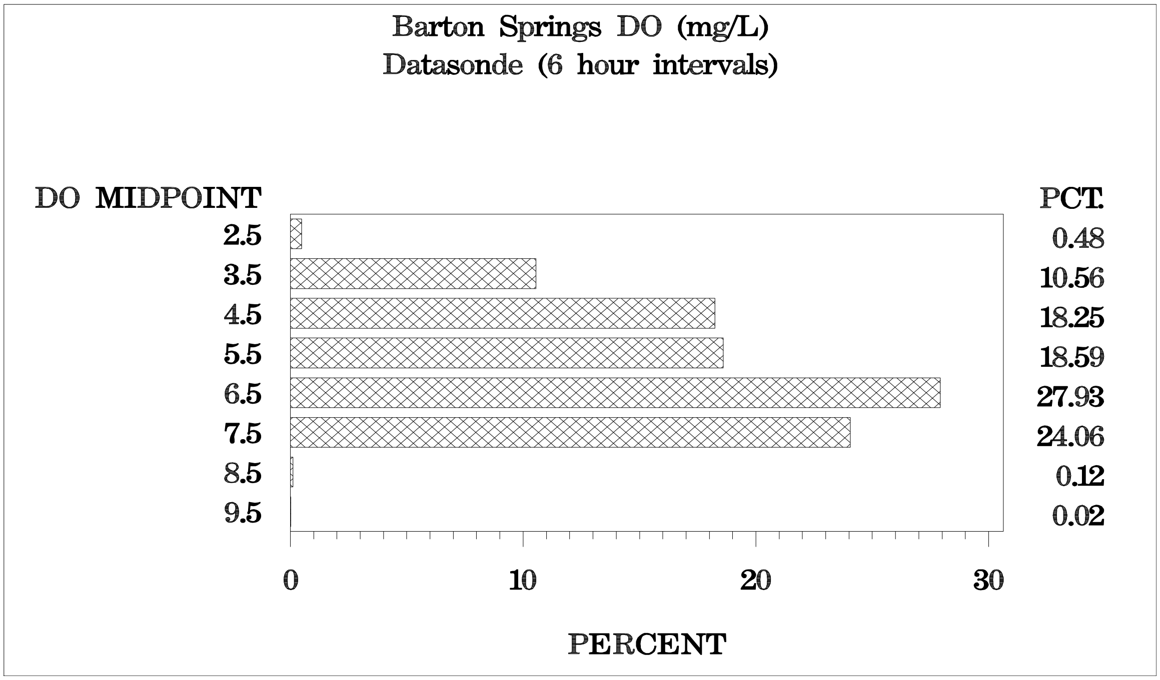


Figure 9 Datasonde Dissolved Oxygen Frequency



Organic Carbon

Organic carbon has increased during storm flow only. The size of the increase in median concentration over the last 25 years is 1.9 mg/L, from 1.5 to 3.4 mg/L. This change is an increase of 127%. Perhaps increased deposition of degradable organic carbon in the aquifer during storm flow may lead to decreases in DO during baseflow when no recharge is occurring. However, this mechanism is an untested inference from the two parameter changes. Scatterplots of these data are provided in Figures 10 and 11.

Sulfate

Sulfate has increased during baseflow when recharge is occurring. Median sulfate concentrations have increased approximately 10.5 mg/L, from 28.3 to 38.8 mg/L. This is an increase of 37% over a 20-year period. Sulfate levels have been found to be fairly consistent indicators of urbanization in much smaller springs in the Jollyville Plateau region. Mean concentrations in rural springs ranged from 12 to 26 mg/L, whereas mean concentrations in newer urban springs ranged from 43 to 59 mg/L (read from graph in COA, 1999). The current median concentrations in Barton Springs lie between these two groups. Again, this increase may be an early indicator of the effects of watershed urbanization that are not reflected in more commonly considered pollutants. Scatterplots of these data are provided in Figures 12 and 13.

Turbidity

Turbidity has increased significantly over time during storm flow. Turbidity is significantly inversely proportional to spring discharge. Sampling has been much more frequent recently – leading to a higher probability of observing extreme events. However, the frequency of high turbidities is such that the observed increase is unlikely to be a sampling artifact. The average increase in storm water turbidity is 1.7 NTU, from 5.3 to 7 NTU. This is an increase of about 32% over the past 20 years. Scatterplots of these data are provided in Figures 14 and 15. It should be noted that the influence of recent data on storm condition results may be significant due to an effort to obtain representation of turbidity over the storm flow hydrograph. This can be compared to previous sampling strategies whereby only single grab samples were obtained for storm events. Replacement of storm event data with median values causes the regression to be non-significant at the 0.05 level; however, the regression is still significant when these events are replaced with the maximum single grab taken over the storm event.

While the changes in turbidity during baseflow are not significant due to the variability of the data and the large number of very low concentrations, some indication exists that change is occurring. Table 3 shows the percent of the turbidity measurements that fell within various ranges for three periods of time. Prior to 1990, under baseflow conditions, 82% of the turbidity levels during recharge were less than 2 NTU and all storm flow turbidities were less than 12 NTU. In the past 5 years 74% of the baseflow turbidity levels during recharge conditions were between 2 and 12 NTU, and 34% of storm flow turbidities were between 12 and 50 NTU. Although short-term turbidity increases are expected during storm conditions as a watershed is

Table 3 Percent of Turbidity Concentrations in Selected Ranges for Three Time Periods

	Baseflow without Recharge		Baseflow with recharge		Storm flow	
Period	**0-2 NTU**	**>2 NTU**	**0-2 NTU**	**>2 NTU**	**0-12 NTU**	**>12 NTU**
1975-1989	100%		82%	18%	100%	
1990-1994	97%	3%	85%	15%	95%	5%
1995-1999	75%	23%	28%	72%	67%	33%

Figure 10 Organic Carbon During Storm Flow

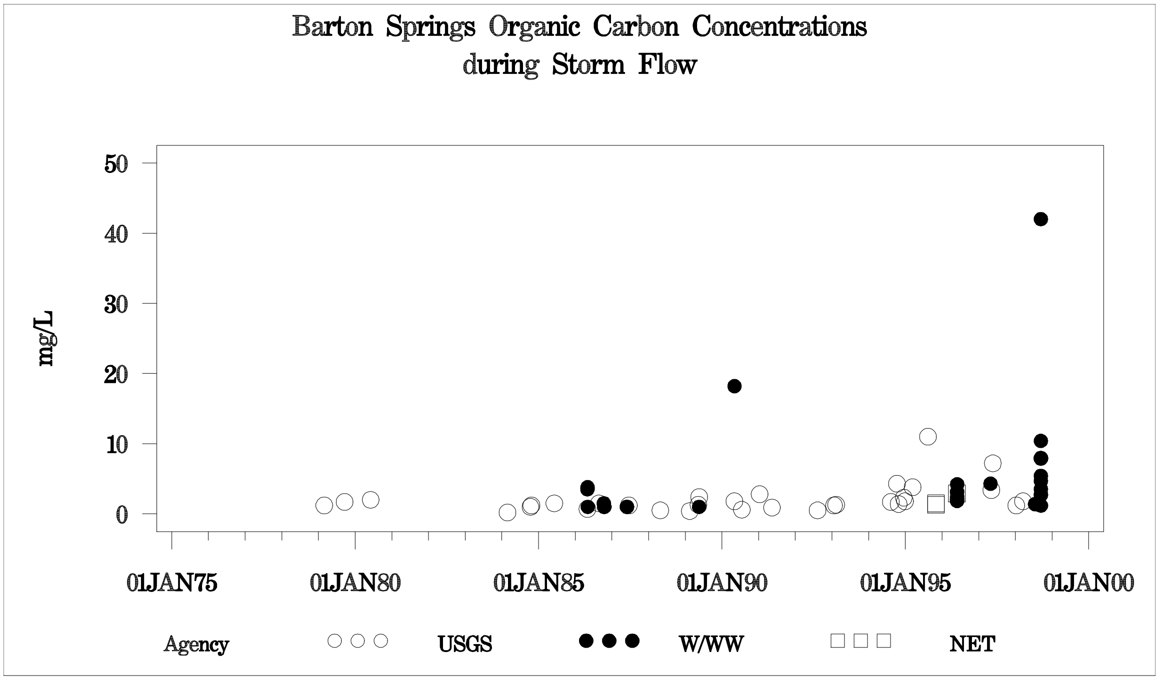


Figure 11 Organic Carbon During Storm Flow Without Outliers

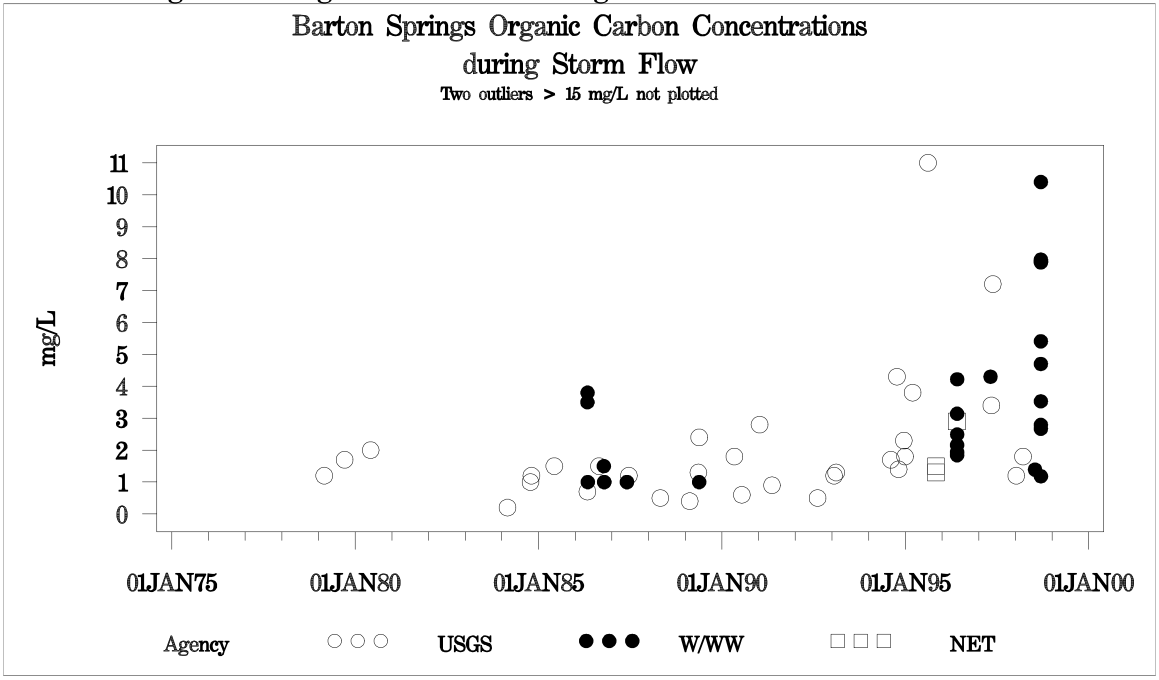


Figure 12 Sulfate During Baseflow With Recharge

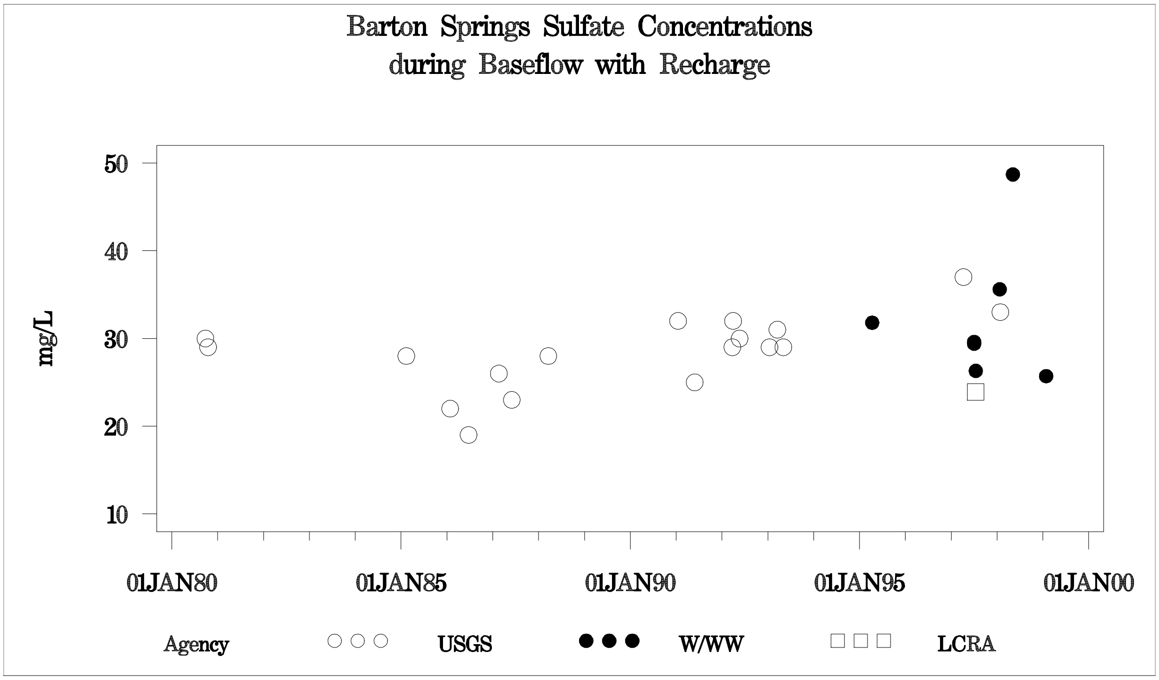


Figure 13 Normalized Sulfate During Baseflow With Recharge

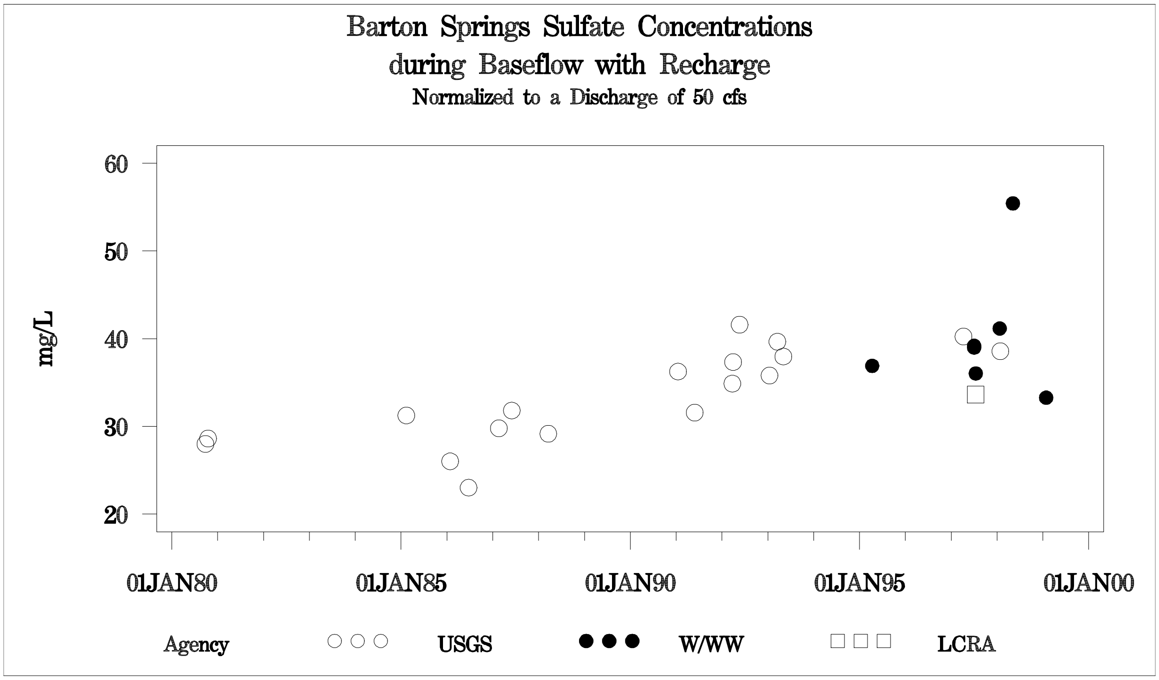


Figure 14 Turbidity During Storm Flow

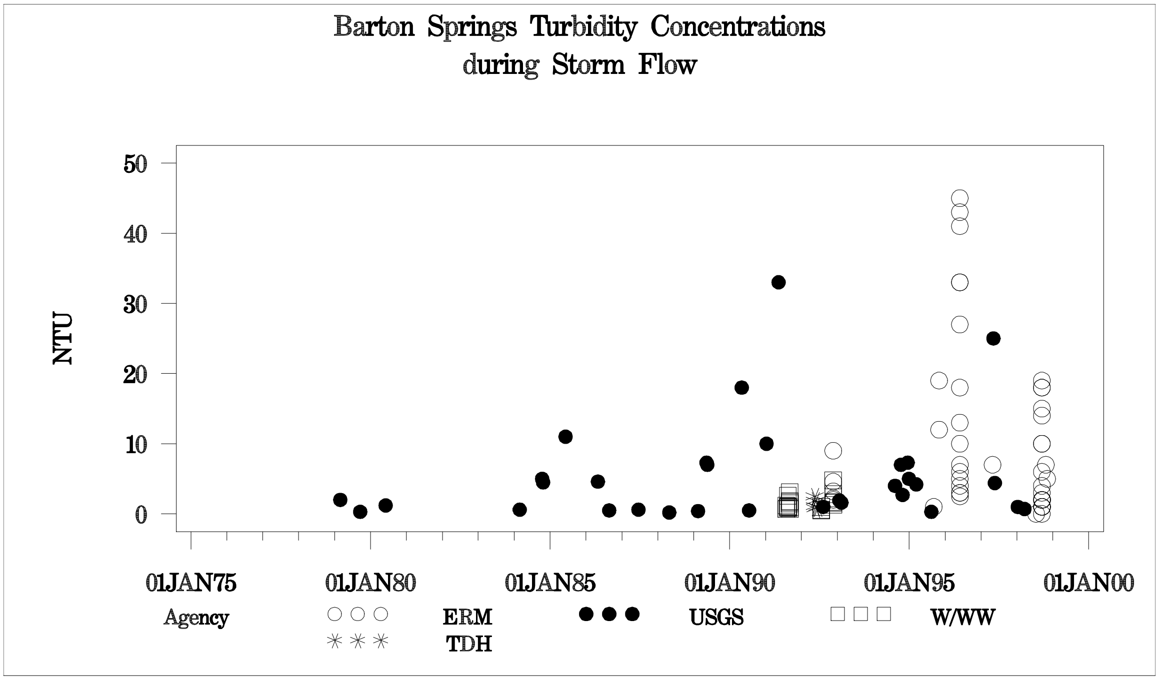
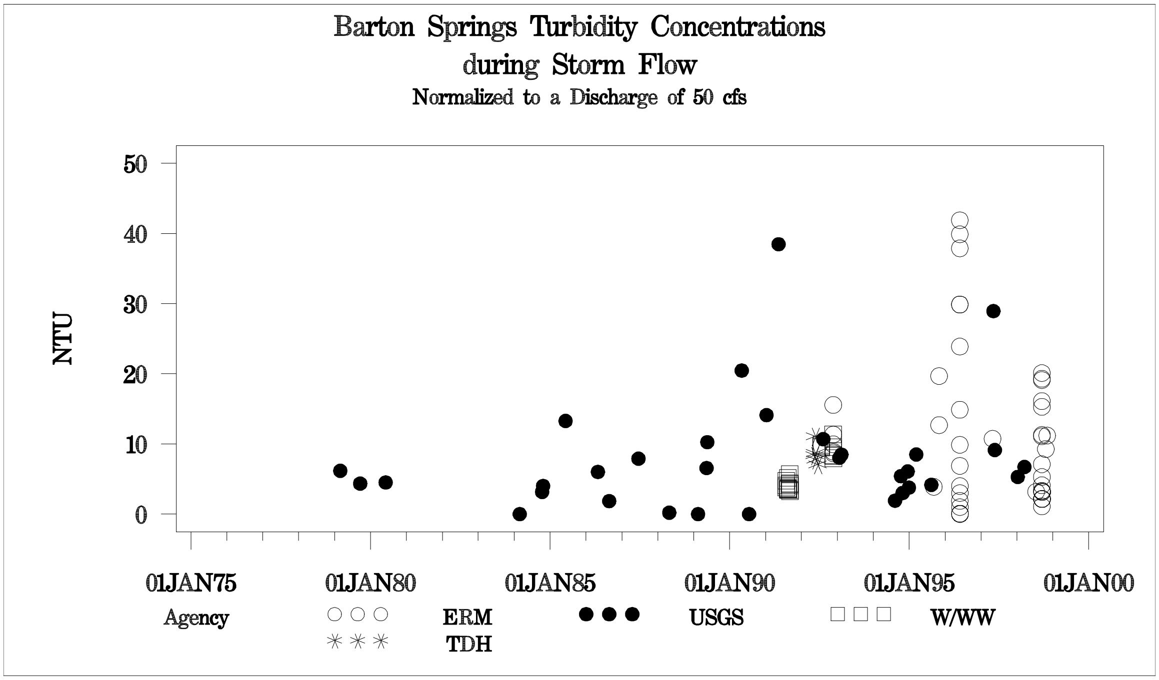


Figure 15 Normalized Turbidity During Storm Flow



urbanized, baseflow increases in turbidity may also be an early indicator of such watershed changes. Also, the inclusion of data removed due to lack of corresponding coliform and TSS data impacts the turbidity regressions. Including these data as baseflow resulted in a significant increasing trend for non-storm, recharge conditions.

ADDITIONAL ANALYSES ON SPRING DATA

Several additional analyses were completed as checks on the validity of the results on parameters and flow conditions that were shown to have significant changes over time in the results presented above. First, the multiple regressions were rerun on two subsets of the data: USGS data and all data prior to 1995. Second, all flow conditions were lumped together and two different regression models were investigated. In one model, the two independent variables were discharge followed by date (the model selected for use in all the analyses discussed previously). In the other model, date was the only independent variable. The regression coefficients for date from these analyses are presented in Table 4.

Trend Analysis on USGS Data

Most of the data prior to 1995 were gathered by the USGS, whereas in recent years most samples have been collected by other agencies. Time trends identified by analyses on all the data may be due to method or lab differences. To investigate this possibility the analyses were rerun on just the USGS data. Significant results provide an important confirmation of the original analyses. If the date regression slope is no longer significant, then additional investigation would be needed. In this situation, method or lab differences should be considered. However, the loss of significance may be due simply to the decrease in number of data points. If this is the case, the slope of the time trend would be expected to be similar to that found on the entire data set. Time trends noted for dissolved oxygen, organic carbon, and sulfate were confirmed by regression on the USGS data, as were time trends for conductivity during baseflow.

Time trends for conductivity during storm flow and turbidity were not significant when only the USGS data were considered. The regression coefficients for date on the USGS data have the same sign and are approximately half the size of the coefficients for the entire data set. This result may imply that the change over time is not as large as indicated by the entire data set, or that with more USGS data the trend will be confirmed, or that the trend does not exist. These parameters under these flow conditions could warrant more investigation.

Trend Analysis on 1975-1994 Data

No significant time trends at the 0.05 level were found when the data from the last 5 years were eliminated. This result would explain why previous analyses did not observe such trends. However, for most parameters and flow conditions, the slopes were similar in magnitude and had the same sign. This would imply that the trends were there but that the number of data points was insufficient to confirm the significance of the trend. The parameters and flow conditions where this was not true were conductivity during storm flow and turbidity. These conditions are also those under which time trends were not confirmed by the analysis on the segregated USGS data.

Trend Analysis on Unseparated Data

Since the split of the data into the three flow categories is imprecise, the multiple regression was run on all flow categories lumped together with discharge and date as the independent variables. In addition, regression with date alone for the independent variable was performed. Significant time trends were identified for dissolved oxygen and conductivity with both regressions. When the data are lumped, no trends are observed for organic carbon, sulfate, or turbidity.

Table 4 Regression Coefficients for Date

Flow Condition	All conditions lumped		Baseflow without Recharge			Baseflow with Recharge			Storm Flow		
Model Independent Variables	date	Discharge and date	Discharge and date	discharge and date	Discharge and date	Discharge and date	discharge and date	discharge and date	Discharge and date	Discharge and date	discharge and date
Data	All	All	All	USGS	1975-1994	All	USGS	1975-1994	All	USGS	1975-1994
Conductivity	0.006	0.006	0.004*	0.006	0.001	0.011	0.014	0.011*	0.005	0.004	-0.003
Dissolved Oxygen	-0.00012	-0.00012	-0.00015	-0.00015	-0.00014						
Organic Carbon									0.0009	0.0004* (not shaded)	0.0002
Sulfate						0.002	0.002	0.002			
Turbidity						Not shaded			0.001*	0.0006	0.0002

Cells are blank when none of the regressions for that parameter and flow condition were significant.
Shaded cells indicate significant regressions at the 0.05 level.
* indicates significance at the 0.10 level.

SUMMARY OF BARTON SPRINGS DATA ANALYSIS

Analysis of long-term water quality records from Barton Springs using two primary data sources now indicates statistically significant changes in water quality that could be related to watershed urbanization. Increasing conductivity, sulfate, turbidity, and total organic carbon trends were noted to be significant. A decreasing trend in dissolved oxygen concentration was also found to be significant. Significant trends were not noted in other parameters that are commonly considered pollutants, such as nutrients and total suspended solids. Significance and presence of trends are variable depending on flow conditions (i.e., baseflow vs. stormflow, recharge vs. non-recharge).

REFERENCES

Allison, Paul D., *Survival Analysis Using the SAS System: A Practical Guide*, Cary, NC: SAS Institute Inc., 1995. 292 pp.

Barrett, M.E., and Charbeneau, R.J. 1996. *A Parsimonious Model for Simulation of Flow and Transport in a Karst Aquifer*: The University of Texas at Austin, Center for Research in Water Resources. Technical Report 269. 149 p.

COA, 1997. *The Barton Creek Report*, COA, DUD, ERM. Water Quality Report Series COA-ERM/1997.

COA, 1999. *Jollyville Plateau Water Quality and Salamander Assessment*, COA, WPD, ERM. Water Quality Report Series COA-ERM/1999-01.

Johns, David A. Personal Communication with Martha Turner concerning dates of recharge condition and storm influenced sampling of COA. City of Austin. Watershed Protection Department. September 3, 1999.

McReynolds, M., and Slade, R. 1986. Barton Springs: A Case Study in Aquifer Contamination and Development of a Groundwater Management Program. City of Austin. Water/WasteWater Department.

Santos and Assoc., Loomis and Assoc., LOK, Tetra Tech and Glenrose Engineering, 1995. *Barton Springs Zone Retrofit Master Plan Study.* Santos and Assoc., Loomis and Assoc., Austin, Texas.

SAS Institute Inc., 1989. SAS/STAT® User's Guide, Version 6, Fourth Edition, Volume 2, Cary, NC, 846 pp.

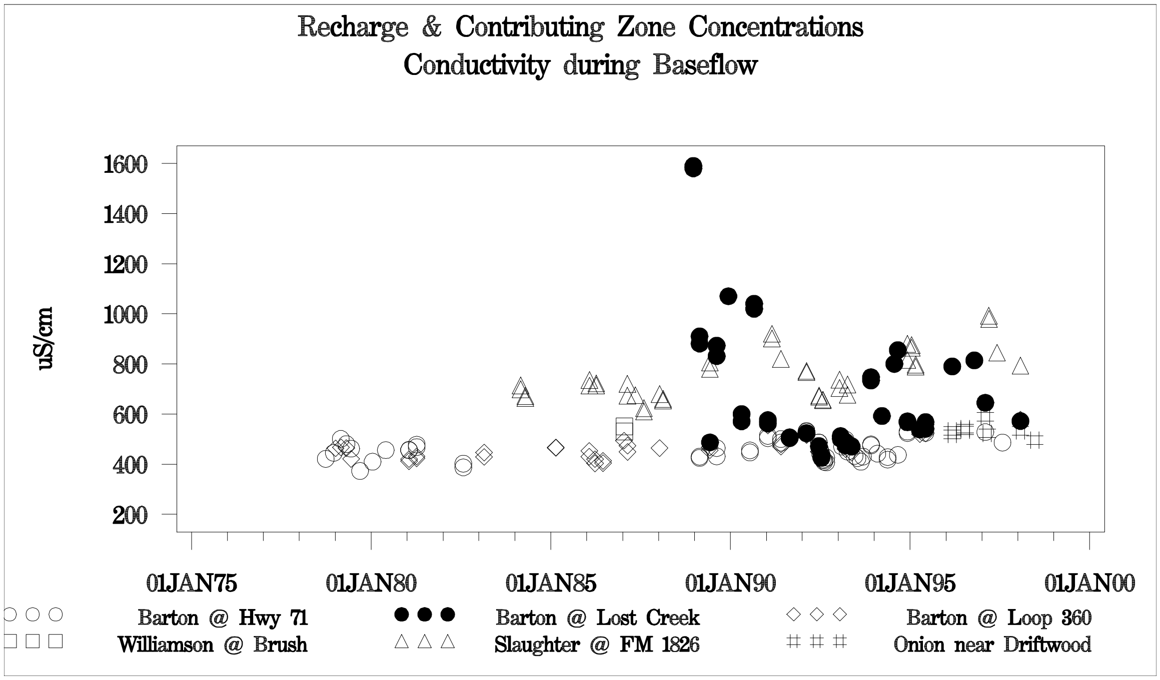
Senger, Rainer K., and Kreitler, Charles W., 1984. *Hydrogeology of the Edwards Aquifer, Austin Area, Central Texas*, Bureau of Economic Geology, Report of Investigations No. 141.

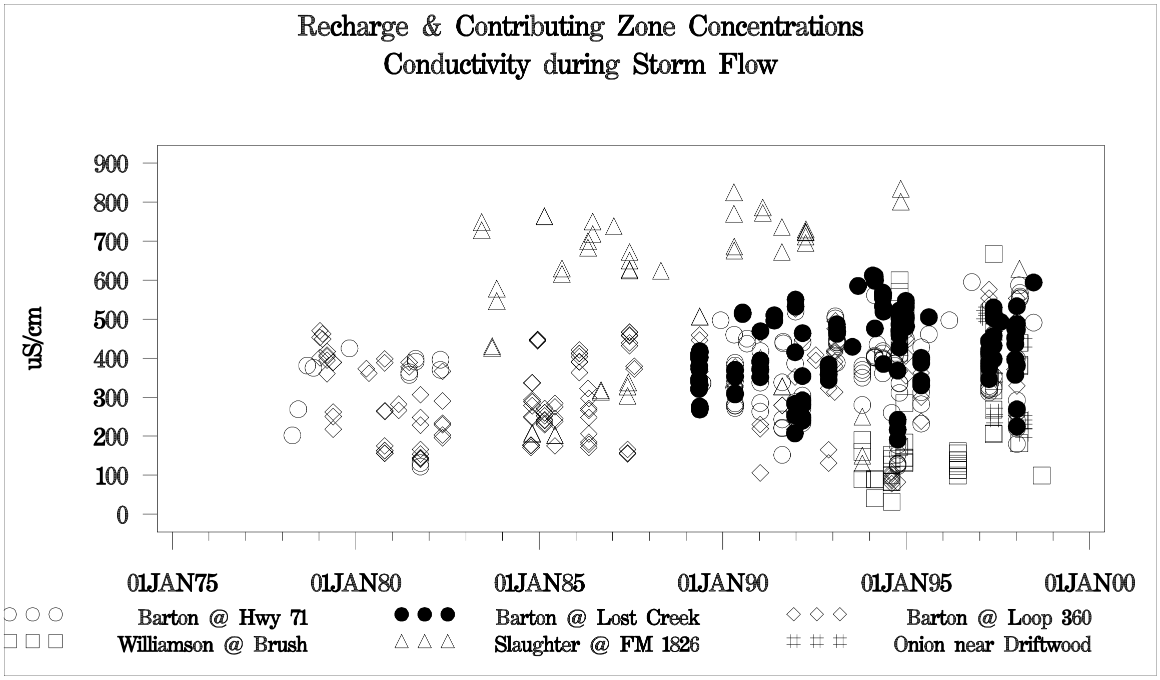
TNRCC 1995. Letter from Mark Jordan, Director Water Quality Policy and Regulation Division to Jana Grote, USFWS concerning proposed listing for the Barton Springs Salamander and absence of material decline in water quality of Barton Springs over 20-year period of nine studies between 1976 and 1994. May 17, 1995.

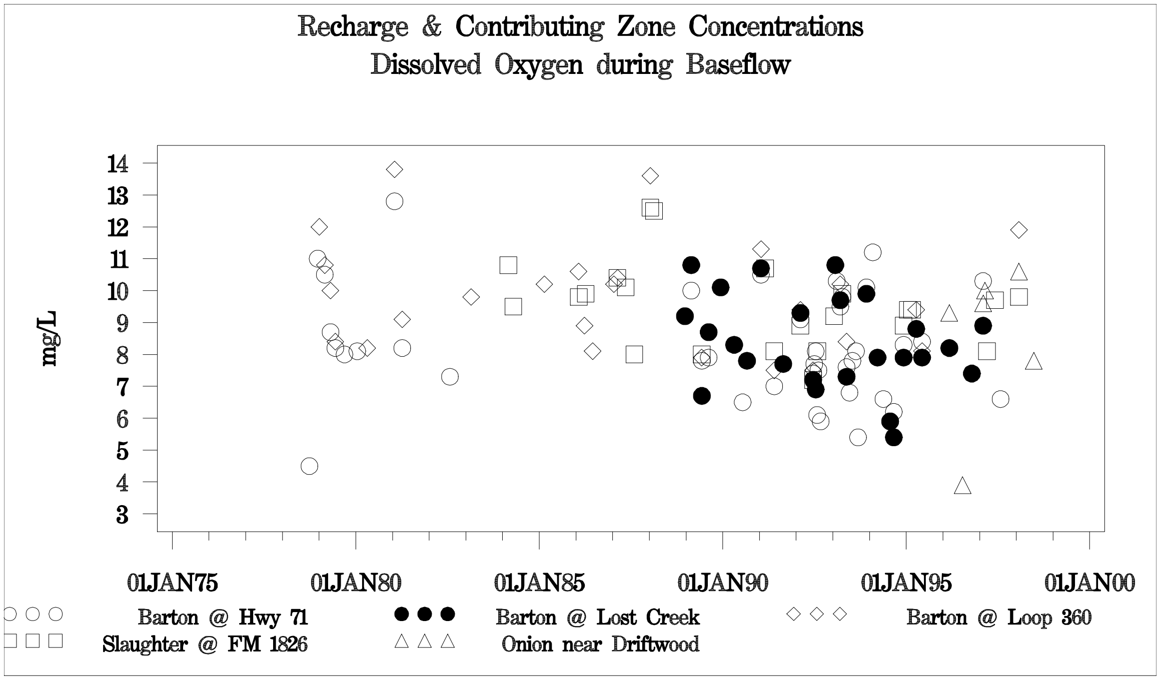
USGS 1986. *Hydrology and Water Quality of the Edwards Aquifer Associated with Barton Springs in the Austin Area, Texas.* USGS, Water-Resources Investigations Report 86-4036.

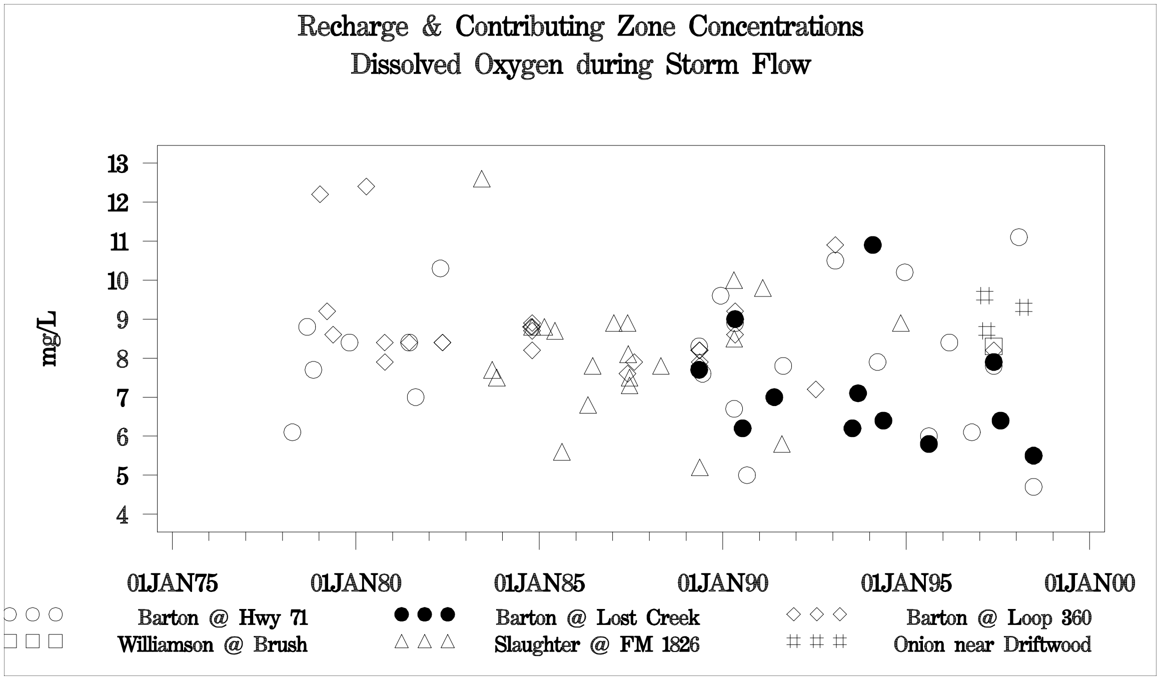
Appendix A
Trends in Creek Concentrations in the Contributing and Recharge Zones

Preliminary investigation of USGS surface water quality data at sites in the contributing and recharge zones indicates that dissolved oxygen, turbidity, and organic carbon are decreasing and sulfate and conductivity are increasing during both storm and baseflow. The direction of the trends over time in the creeks matches those in Barton Springs for DO, sulfate, and conductivity. However, the trends for turbidity and organic carbon in the creeks are in the opposite direction from the trends in Barton Springs. Trends that are significant when the data from all the sites is combined may not be significant when the data from each site are considered separately. In some cases even the direction of the trend is different at a particular site. For example, both sulfate and conductivity have decreased, from abnormally high values, in Barton Creek at Lost Creek Blvd. during baseflow, whereas the trend in the combined data is increasing. These data are still under investigation, and the results on the combined data may also be influenced by inconsistent frequency and timing of samples between sites. Plots of the data are included as follows in this Appendix for information and review.

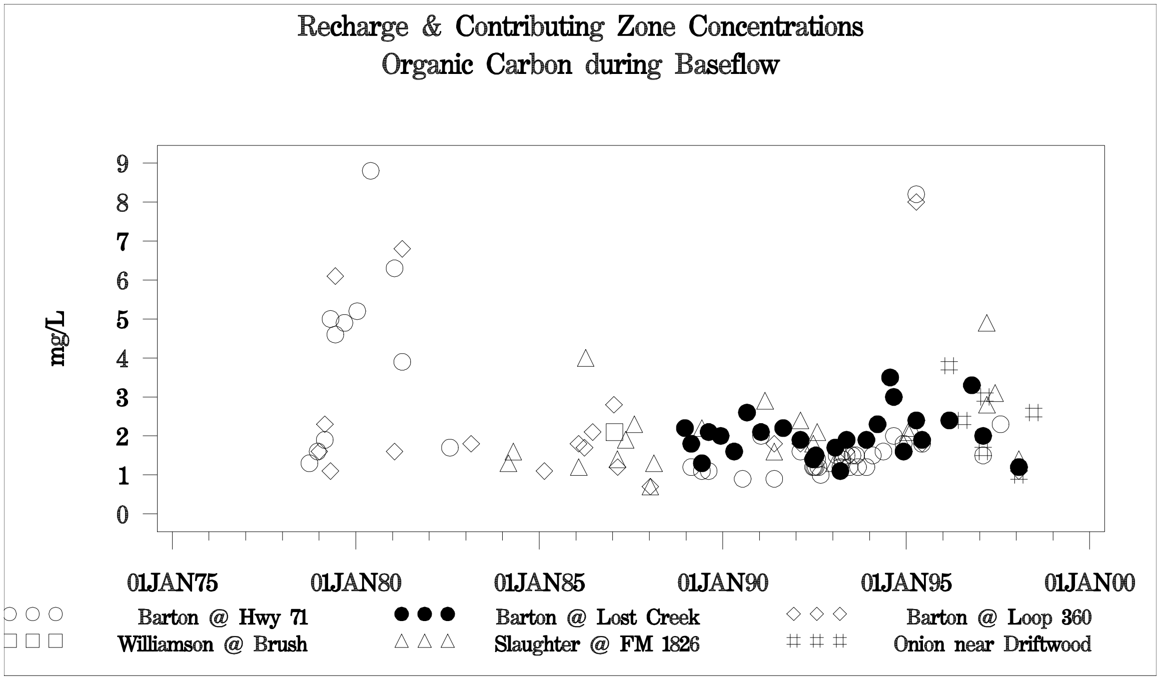



Recharge & Contributing Zone Concentrations
Conductivity during Storm Flow
uS/cm
900
800
700
600
500
400
300
200
100
0
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
Barton @ Hwy 71
Barton @ Lost Creek
Barton @ Loop 360
Williamson @ Brush
Slaughter @ FM 1826
Onion near Driftwood

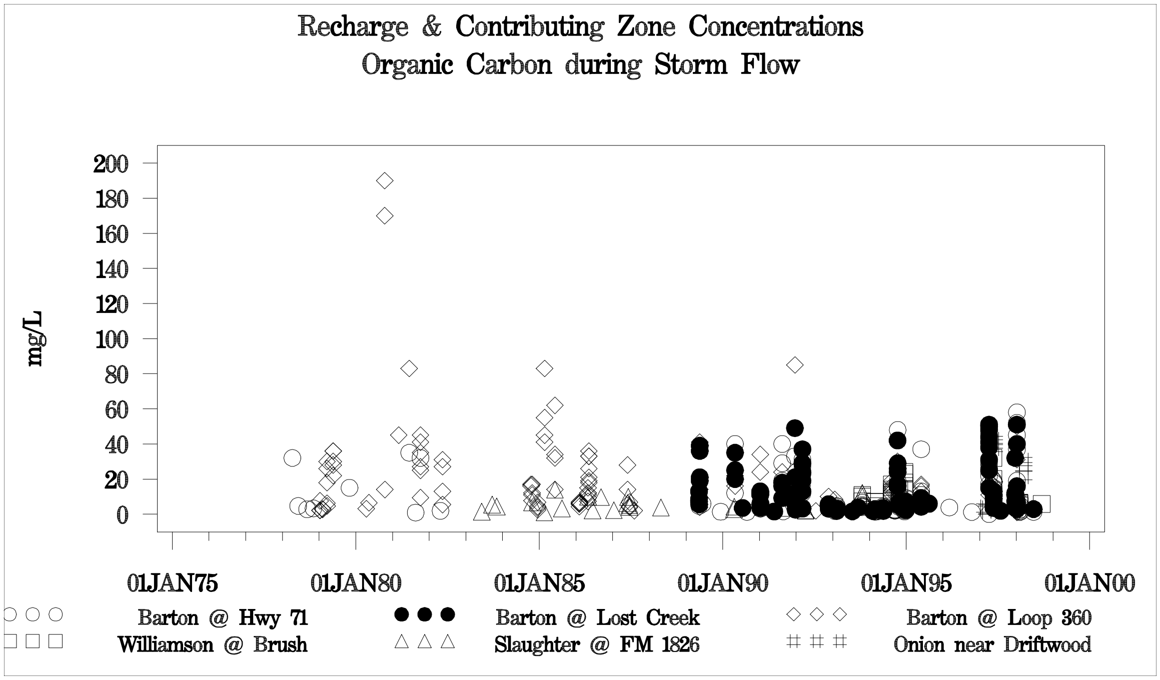

Recharge & Contributing Zone Concentrations
Dissolved Oxygen during Baseflow
mg/L
14
13
12
11
10
9
8
7
6
5
4
3
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
Barton @ Hwy 71
Barton @ Lost Creek
Barton @ Loop 360
Slaughter @ FM 1826
Onion near Driftwood



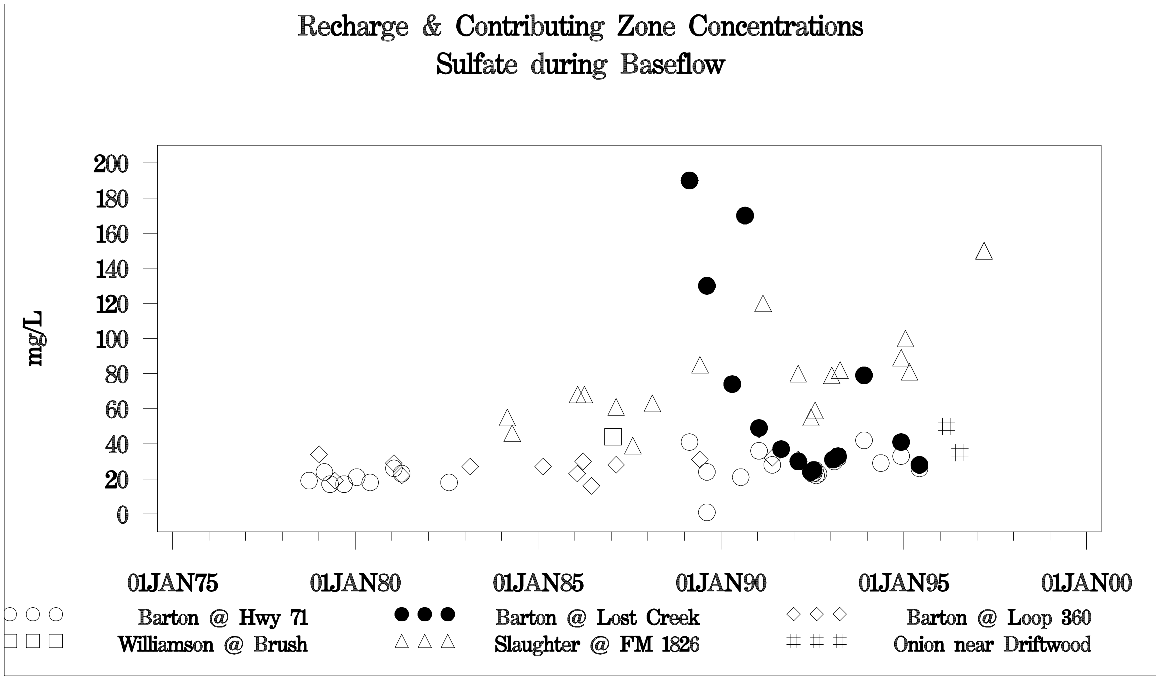
Recharge & Contributing Zone Concentrations
Dissolved Oxygen during Storm Flow
mg/L
4
5
6
7
8
9
10
11
12
13
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Williamson @ Brush
△ △ △ Slaughter @ FM 1826
Onion near Driftwood



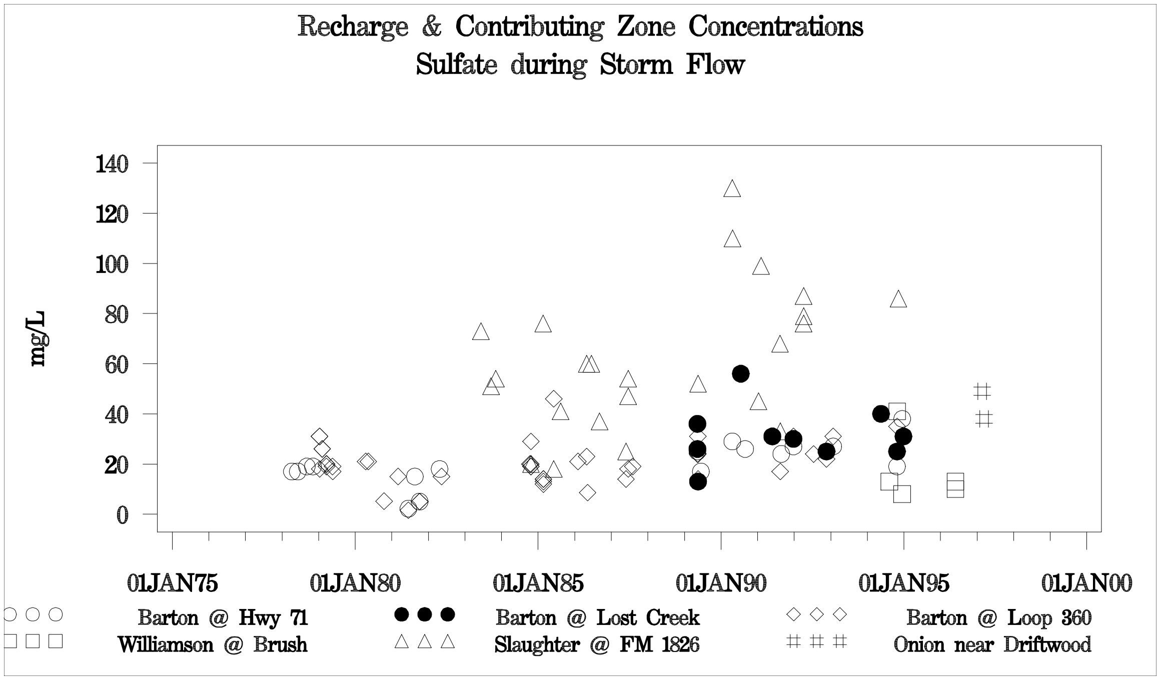
Recharge & Contributing Zone Concentrations
Organic Carbon during Baseflow
mg/L
0
1
2
3
4
5
6
7
8
9
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Williamson @ Brush
△ △ △ Slaughter @ FM 1826
Onion near Driftwood

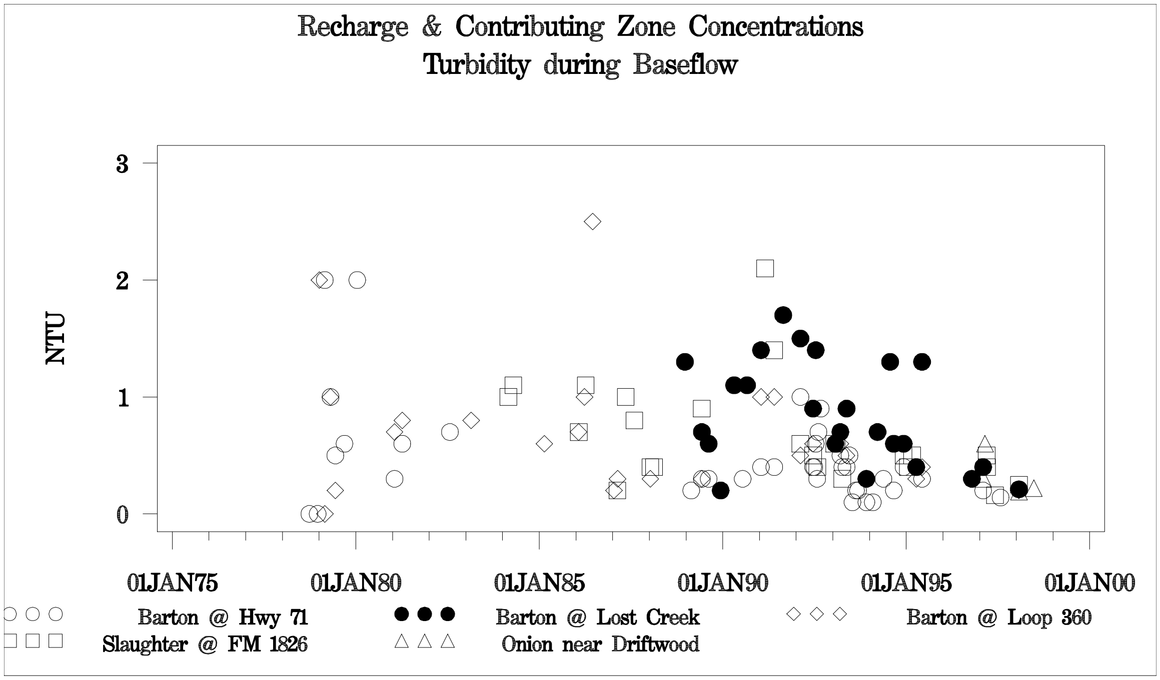


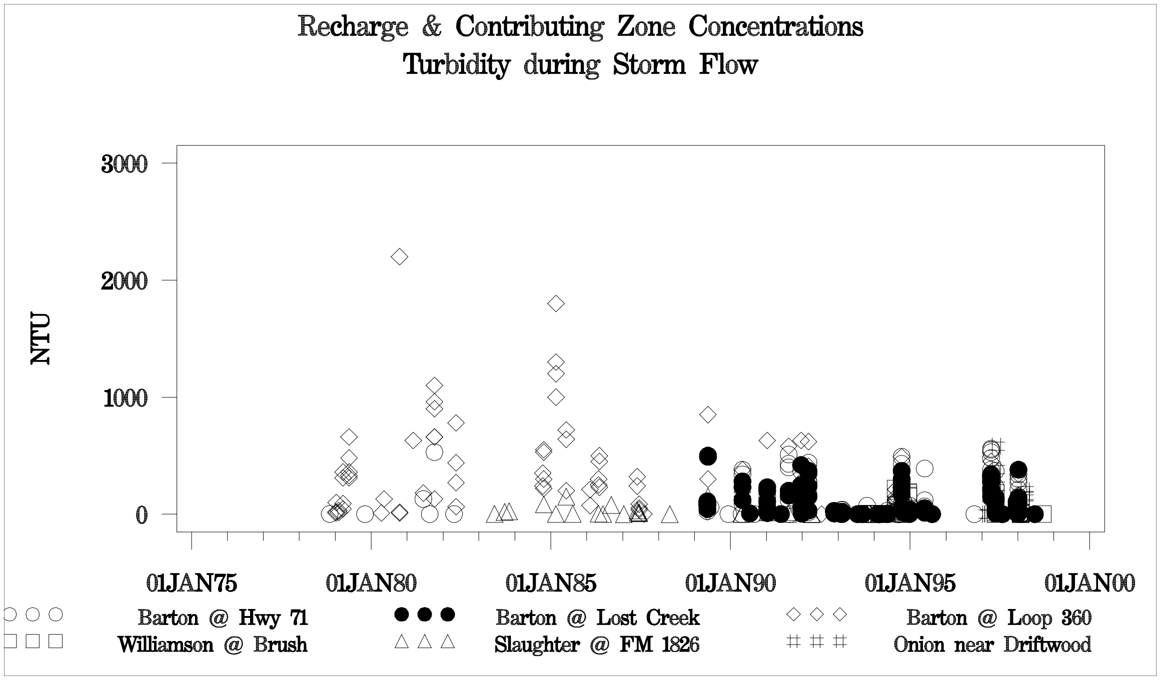
Recharge & Contributing Zone Concentrations
Organic Carbon during Storm Flow
mg/L
200
180
160
140
120
100
80
60
40
20
0
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Williamson @ Brush
△ △ △ Slaughter @ FM 1826
♯ ♯ ♯ Onion near Driftwood



Recharge & Contributing Zone Concentrations
Sulfate during Baseflow
mg/L
200
180
160
140
120
100
80
60
40
20
0
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Williamson @ Brush
△ △ △ Slaughter @ FM 1826
♯ ♯ ♯ Onion near Driftwood


Recharge & Contributing Zone Concentrations
Sulfate during Storm Flow
mg/L
140
120
100
80
60
40
20
0
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Williamson @ Brush
△ △ △ Slaughter @ FM 1826
Onion near Driftwood


Recharge & Contributing Zone Concentrations
Turbidity during Baseflow
NTU
3
2
1
0
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Slaughter @ FM 1826
△ △ △ Onion near Driftwood


Recharge & Contributing Zone Concentrations
Turbidity during Storm Flow
NTU
3000
2000
1000
0
01JAN75
01JAN80
01JAN85
01JAN90
01JAN95
01JAN00
○ ○ ○ Barton @ Hwy 71
● ● ● Barton @ Lost Creek
◇ ◇ ◇ Barton @ Loop 360
□ □ □ Williamson @ Brush
△ △ △ Slaughter @ FM 1826
Onion near Driftwood

Appendix B
Additional Analyses on Nitrate Concentrations in Barton Springs

Early Nitrate Data (1937 – 1971)

Analysis of COA, ATCHD, and USGS data from 1975-1999 showed no trends in nitrate concentrations. The data included in these analyses were selected because they were both comprehensive and collected by agencies with QA/QC procedures, leading to a greater degree of confidence in the analytical results. However, additional nitrate data are available from earlier periods. Nitrate concentrations were measured 10 times between 1937 and 1973, as indicated in Table B-1. These 10 samples were collected by several different agencies. The QA/QC information for these samples is unavailable; thus the quality of this data is unknown. It has been suggested that these concentrations may be high estimates of nitrate since the holding times may have been longer than is currently allowed and the measured concentration may be total nitrogen rather than nitrate. Discharge levels were recorded for these samples, and storm and recharge conditions were estimated from daily rainfall at Austin airports (see Table B-1).

Table B-1. 1937-1973 Nitrate Data with Flow Condition Estimates

DATE	RAIN	Storm	Recharge	DISCHARGE (cfs)	Qualifier	Dissolved NO_3 mg/L as N
August 23, 1937	No	No	No	32	<	1.13
September 7, 1937	Maybe - 4 days after 2"	Yes	Yes	31	<	1.13
September 9, 1937	No - 6 days after 2"	No	No	31	<	1.13
October 27, 1939	Yes - 2 days after 1.2 "	Yes	Yes	16	<	1.13
November 9, 1939	No	No	No	12	<	1.13
October 1, 1941	Yes? - 1.9" on date	Yes	Yes	55		0.99
June 10, 1948	No	No	No	19		1.02
January 18, 1955	Yes - 0.21" on date, 0.85" on previous day	Yes	Yes	21		1.02
April 22, 1971	No	No	No	30		1.47
February 6, 1973	No	No	No	69		1.24

Three separate analyses done on the expanded data set with these early nitrate concentrations included: 1) Regression on the entire data set, 2) Analysis of variance on period means under low Barton Springs discharge and baseflow conditions, and 3) Estimation of the probability that the nitrate concentration distribution has not changed over time.

Regression on the Expanded Data Set: 1937-1999

When the early data are included in the regression analyses, significant trends for baseflow without recharge and storm flow categories are found (Table B-2). No early data are available in the baseflow with recharge category.

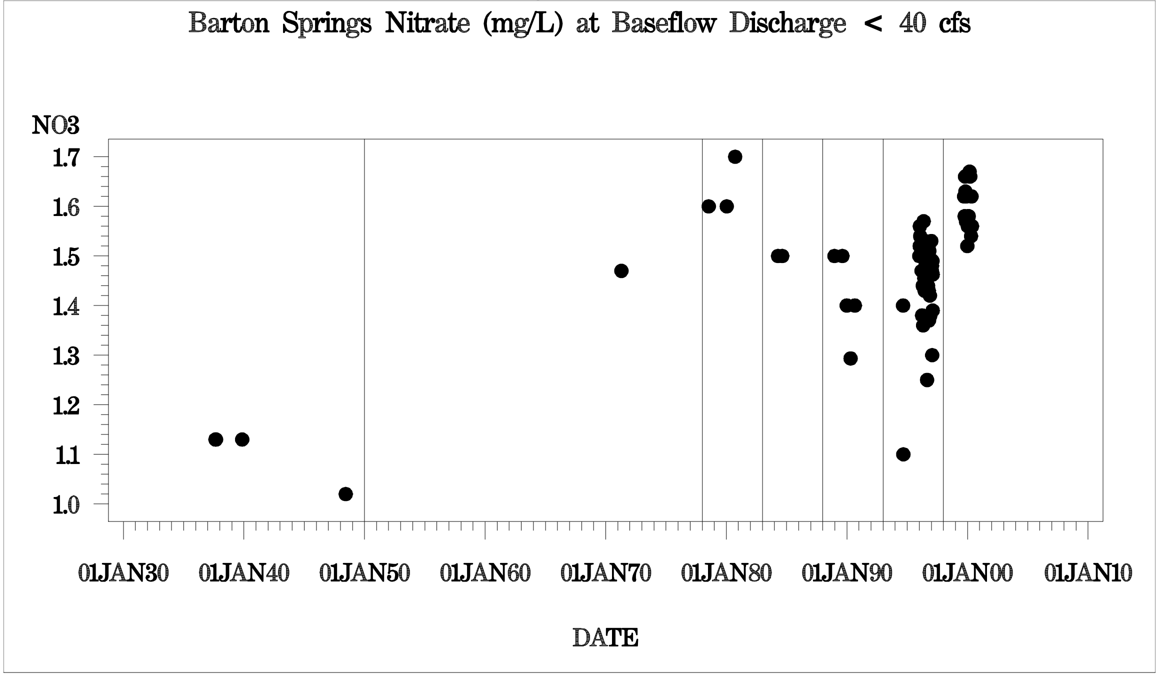
Table B-2
Regression R-Squares, Model and Coefficient Probabilities, and Coefficient Estimates

				Regression Coefficients			
		Model		Discharge		Date	
Parameter	**Flow Condition**	**Pr > F**	**R-Square**	**Pr > |t|**	**Estimate (Std. Error)**	**Pr > |t|**	**Estimate (Std. Error)**
Nitrate	Baseflow without Recharge	0.0007	0.11	0.0737	-0.00085 (0.00047)	0.0002	0.00001 (0.000003)
	Baseflow with Recharge	No 1937-1973 data					
	Storm Flow	0.0110	0.10	0.0085	-0.0029 (0.001)	0.0785	0.00001 (0.000007)

Baseflow Concentrations At Low Discharge Levels

Examination of nitrate concentrations under low discharge levels in 1999 showed a slight increase over levels in 1996 under similar flow conditions. To better examine the hypothesis that nitrate levels are increasing under low discharge conditions, nitrate data from 2000 were added to the 1937-1999 data set. Nitrate concentrations during baseflow with discharge levels less than 40 cfs are plotted in Figure B-1.

Figure B-1.



The recent data were divided into 5-year periods, and the early data into longer periods (see Figure B-1). Analysis of variance confirmed that the nitrate concentrations in the different periods are not equal ($P < 0.0001$). To determine which periods were significantly different, five contrasts were investigated:

Table B-3. Period Differences as determined from ANOVA contrasts

Contrast	**Pr > F**
Before 1950 vs. after 1950	P < 0.0001
Before 1998 vs. after 1998	P < 0.0001
1993-1997 vs. 1998-2000	P < 0.0001
1978-1982 and 1998-2000 vs. 1983-1997	P < 0.0001
1978-1982 vs. 1998-2000	P = 0.4418

The nitrate levels before 1950 were significantly lower than the lumped data after 1950. Also the nitrate levels after the start of 1998 were significantly higher than the lumped concentration levels before 1998. The nitrate levels after the start of 1998 were significantly higher than during the previous 5-year period, 1993-1997, when flow conditions, sampling frequencies, and lab and analysis methods were relatively consistent. However, concentrations in the 5-year period from 1978 through 1982 were not significantly different from those in 1999 and 2000. It should be noted that a major sewer line failure occurred and was fixed in 1982. Data from 1981 and 1982 was removed from the analysis. However, the start date for the sewer line failure is not known. Adequate data exist in 1981 and 1982 to demonstrate that water quality was affected by sewage, but data from 1980 are sparse and the water quality signature is not so clear. The nitrate concentrations may have been affected by the sewer line break, but they may not have been. The single low-discharge storm flow sample taken during the 1978 through 1982 period had a higher nitrate level than the baseflow samples. This result may indicate sewer line problems since nitrate concentrations typically decrease during storm flow. However, this cannot be proven in retrospect, and thus it cannot be shown with certainty that nitrate concentrations at low discharge have increased during the last 25 years.

Probability That Nitrate Concentration Distribution Has Not Changed Over Time

All nitrate concentrations prior to 1960 were less than 1.13 mg/L. However, similarly low nitrate concentrations can be observed today. Was the distribution of nitrate concentrations prior to 1960 really the same as today's distribution? It is possible but the probability is not high. Table B-4 shows the proportion of nitrate concentrations above and below 1.13 mg/L as N for both time periods.

Table B-4. Number of nitrate samples above and below 1.13 mg/L for two time periods

Time Period	Nitrate Level	Baseflow without recharge	Baseflow with recharge	Storm Flow
Before 1960	< 1.13 mg/L	4	No data	4
	> 1.13 mg/L	0	No data	0
After 1960	< 1.13 mg/L	7	27	22
	> 1.13 mg/L	116	41	67

In the pre-1960 period only four samples were available for each of two flow conditions: baseflow without recharge and storm flow. The probability that all four samples would be below 1.13 mg/L if the distribution were similar to the post-1960 distribution is $(7/123)^4 = 0.0000105$ or approximately 1 in 100,000 for baseflow without recharge. For storm flow the probability is $(22/89)^4 = 0.0037$, or approximately 1 in 300 for storm flow. These probabilities that the nitrate distribution has not changed over time are relatively small and thus it appears safe to say that nitrate concentration have increased over time.