A Statistical Analysis of Wastewater Effluent Potential Impacts on the Colorado River Downstream of Austin

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Abstract

Long term water quality data has been collected from samples along the Colorado River at five locations downstream of Longhorn Dam. These sampling locations were placed to determine the effects of effluent discharged from two of the City of Austin wastewater treatment plants. A statistical analysis on the data was performed looking at trends in space and in time. Results from this analysis show that samples located downstream from the discharge points were higher in concentrations of ammonia, chloride, nitrate, phosphorus, and sulfate than samples located upstream. Furthermore, differences between the sampled locations were identified for E. coli, pH, dissolved oxygen (DO), conductivity, and total dissolved solids (TDS). Analysis showed no increasing trend in time over the past 12 years; however, flow was seen to be a complicating factor in determining trends of some of the water quality parameters. The results from the samples were compared to surface water quality standards. Nitrate-Nitrogen, DO, and total phosphorus parameters did not meet the applicable standards in the Colorado River below the City of Austin wastewater discharge points.

Introduction

The City of Austin ("City") currently owns and operates two major wastewater treatment plants located in eastern Austin. These facilities treat wastewater to standards set by the Texas Commission on Environmental Quality and discharge the effluent directly to the Colorado River under their Texas Pollutant Discharge Elimination System (TPDES) permits (Texas Commission on Environmental Quality, 2014). The discharged effluent is treated to regulatory levels of such physio-chemical characteristics as biological oxygen demand (BOD), total suspended solids (TSS), ammonia-nitrogen (NH_3-N), *E. coli*, chloride, pH, and other parameters. However, even within these regulated levels, the potential for impact on the ecology of the receiving stream exists. No limits for nutrients other than ammonia-nitrogen are currently in the City permits; however, monitoring for total nitrogen and total phosphorus is required.

In recognition of the impact of effluent on biological organisms, the EPA has published a draft chronic numerical criteria of 0.26 mg/L for NH_3-N at standard pH and temperature in freshwater where mussels are present (EPA, 2009). However, Duncan and Nobles (2013) demonstrated that lower growth and survival rates may occur for freshwater mussels in contact with treated wastewater effluent containing ammonia-nitrogen concentrations less than 0.26 mg/L. The current permit limit for ammonia-nitrogen is 2 mg/L for both City wastewater treatment plants (WWTP).

Potential eutrophication of a local stream was investigated by Turner (2012), who modeled the impacts of effluent from a wastewater treatment plant on the South Fork San Gabriel River using the Water Quality Analysis Simulation Program (WASP) model and found that algae levels may increase with total phosphorus levels as low as 0.1 mg/L and with a low discharge volume to stream flow ratio. Similarly, Richter (2010 and 2012) produced WASP models that predicted gross estimates of algal growth under various flow regimes.

Most of the studies discussed, however, examined the effects of smaller wastewater treatment plants on smaller streams in the area. The impacts of wastewater effluent on the ecology of the larger Colorado River are still uncertain. This uncertainty is confounded with the highly variable flow in the Colorado River. Further, the Lower Colorado River Authority (LCRA) is in the midst of changing its Water Management Plan (WMP). Prior to 2010, the LCRA operated its WMP to release more flow in the summer months (April- September) than the winter months (October- March). With the continued drought in central Texas, the LCRA has now significantly restricted its flow releases in the winter months further disrupting the flow regime. Duncan, Scoggins, and Jackson (2011) investigated the distribution of freshwater mussels along the Colorado River and found that temperature and flow disruptions can also inhibit mussel recruitment.

More stringent effluent limits were met by the City when the South Austin Regional WWTP (SAR) went online and upgrades were made to Walnut Creek WWTP in the late 1990's. These effluent limits and plant upgrades seem to have improved conditions over time. By 2000, the Austin Chronicle (Oko, 2000) had reported that the "1999 State of the River report released by the LCRA rates Lake Austin and Town Lake a consistent eight (out of a possible 10) with regard to river health. The portion of the river running between Austin and Columbus, about 100 miles downstream, rates an 'excellent' nine out of 10."

This report seeks to provide a step in the understanding of the Colorado River system due to wastewater effluent. First, an evaluation is needed on whether an impact from the effluent discharge from the two major wastewater treatment plants to the Colorado River exists. This evaluation can come from assessing the long term impacts of the wastewater effluent on the physical and chemical aspects of the river. To that end, Austin Water has been monitoring the stream for nutrient and other chemical and physical data for over twelve years. Furthermore, it has been collecting this data at locations both upstream and downstream of its effluent outfalls to determine whether spatial gradients exist. This data was collected for internal use, and was not submitted to the TCEQ through CRP or required for permit compliance by TCEQ. The objectives of this report are to evaluate the existing data collected and determine:

1) whether differences exist among the monitoring locations (upstream locations vs. downstream of the outfall locations);
2) whether a trend exists in time; and
3) whether TCEQ's assessment criteria would classify this river segment as "impaired" under the Clean Water Act Sections 305(b) and 303(d).

Methods

The data used for this report come from samples obtained by Austin Water, which measures concentrations from fifteen water quality parameters at five monitoring sites on a monthly basis. Although Austin Water continues to obtain water quality samples, this report uses the data to those collected from October 2002 to February 2013. The total number of samples analyzed amounted to a little over one hundred per site for 15 water quality parameters. The five monitoring sites were denoted by an "Area Number" and are described in Figure 1 below.

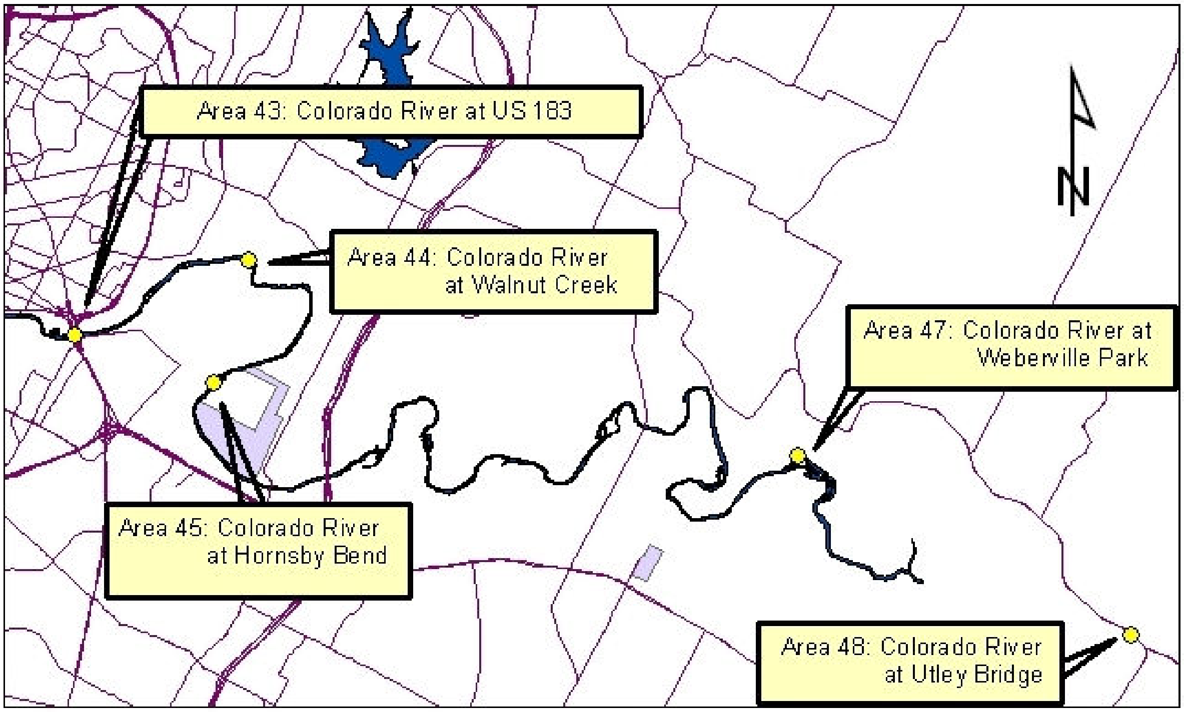

Figure 1: Location of Sampling Sites

The location of the wastewater discharge points is shown (Figure 2 below) in red with the respective Texas Pollution Discharge Elimination System (TPDES) wastewater discharge permit number along with the sampled sites in yellow. The two main sources of treated effluent come from the Walnut Creek Wastewater Treatment Facility (TPDES Permit No. WQ10543-011) and the South Austin Regional Wastewater Treatment Facility (TPDES Permit No. WQ10543-012). Each of these sources has a 75 million gallon per day (MGD) discharge limit. The minor sources of treated effluent are included in this figure for completeness along with the location of the discharge points for decommissioned wastewater treatment plants, such as Govalle Wastewater Treatment Facility. Table 1 below provides the name, permit number, and effluent discharge limit for each of the active treatment plants.

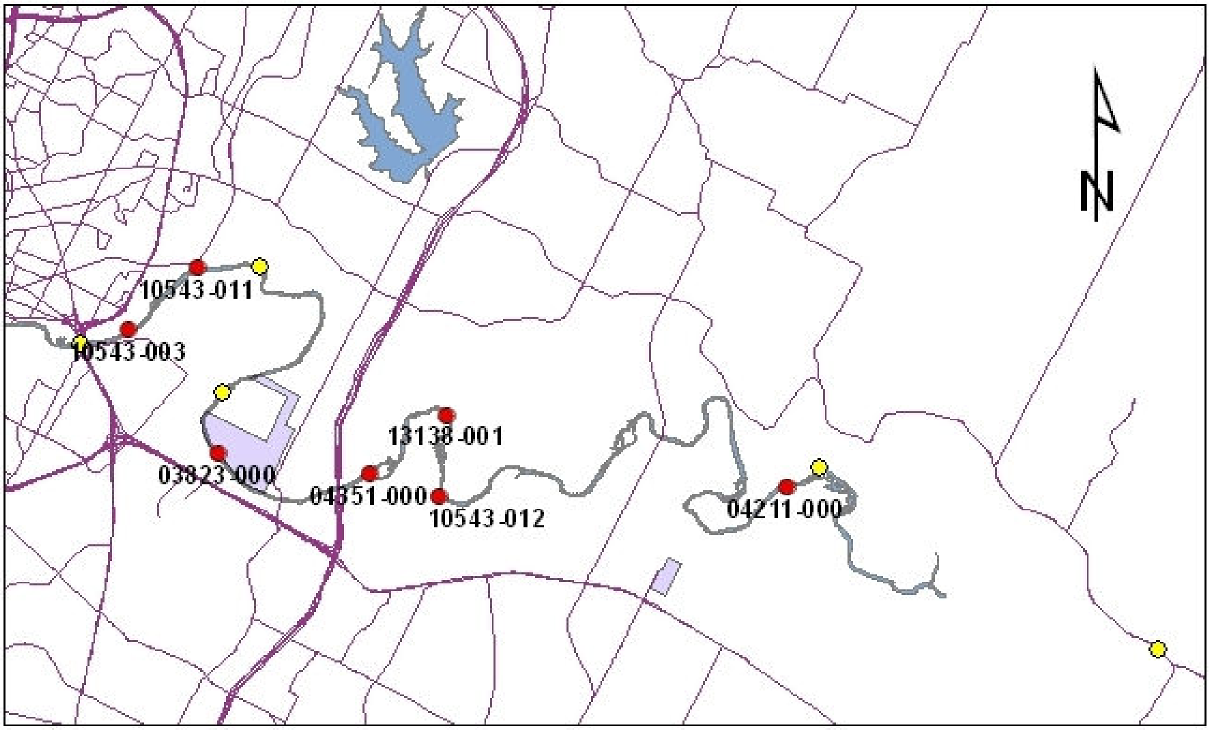

Figure 2: Location of Discharge Outfalls (in red) with Permit Numbers Beneath the Points

The locations of the sampled sites relative to the discharged sites can be used to investigate the impact of the effluent on the Colorado River, as well as its potential recovery, in the case of Area 48, which is located downstream of all the sampling locations and discharge points.

Table 1: Listing of the TCEQ Permitted Wastewater Discharge Points along the Colorado River

Permit No.	Name	Comment
10543-003	Govalle WWTP	Decommissioned in Oct. 2006
10543-011	Walnut Creek WWTF	Daily Ave. Flow < 75 MGD
03823-000	Hornsby Bend WWTP	Permit Superseded in March 2000
04351-000	Sandhill Energy Center	Daily Ave. Flow < 1.3 MGD
13138-001	Austin Colony WWTF	Daily Ave. Flow < 0.90 MGD
10543-012	South Austin Regional WWTF	Daily Ave. Flow < 75 MGD
04211-000	Bastrop Energy Center	Daily Ave. Flow < 2.0 MGD

Table 2 below contains the list of the fifteen water quality parameters measured for collected samples. In addition to this, flow records of the discharge from Lady Bird Lake were obtained from United States Geological Survey's gage number 08158000 to look for correlations between flow and water quality. Figure 3 below shows the distribution of flows used in the analysis. In all, over 8000 data points were obtained and used in this analysis. As with any extensive long term data collection, irregularities in the data were bound to exist. In this case, the complexity of the data consisted of missing values and multiply-censored data due to varying reporting limits. This added an extra layer of complexity to the statistical analysis appropriate to the data set.

Table 2: Listing of Water Quality Parameters

Nutrient Parameters	Physical Parameters	Bacterial Parameters	Particulate Parameters
Ammonia	Chemical Oxygen Demand (COD)	*E. coli*	Total Dissolved Solids (TDS)
Chloride	Conductivity		Total Suspended Solids (TSS)
Nitrate	Dissolved Oxygen (DO)		Volatile Suspended Solids (VSS)
Sulfate	pH		
Total Phosphorus	Temp		
Total Organic Content (TOC)			

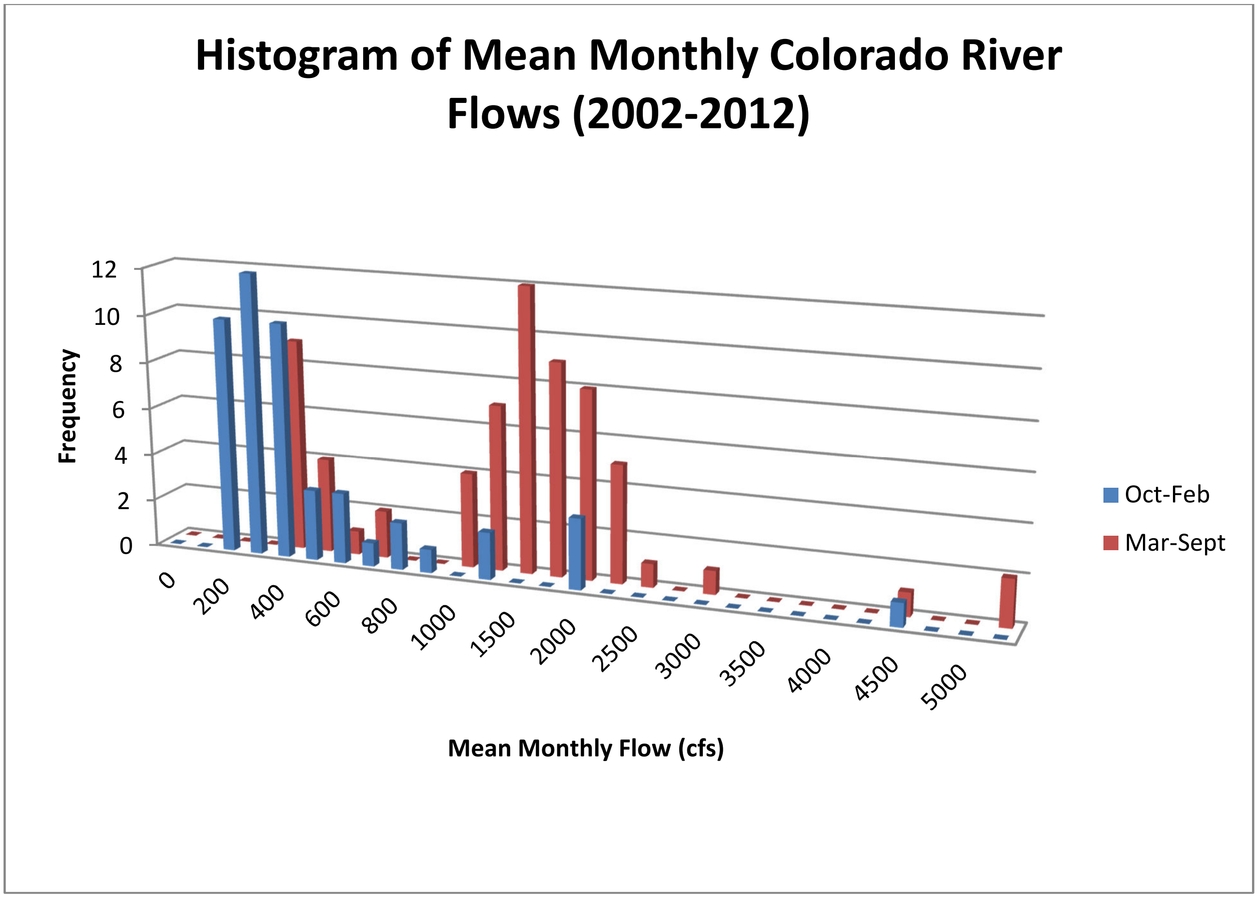

Figure 3: Histogram of Mean Monthly Colorado River Flows from 2002-2012

Statistical Analysis

To meet the objectives of this report, two types of statistical analysis were performed on the data. To look at whether differences existed among the sampling locations, an Analysis of Variance (ANOVA) was conducted on the fifteen water quality parameters (and MANOVA for parameters that were correlated). To examine temporal trends in the data, a second type of analysis, Vector AutoRegressive (VAR) model (Cowpertwait and Metcalfe, 2009), was conducted. This model looks at correlating trends among multiple variables. For the third objective, no statistical analysis was done to determine whether this river segment could be considered impaired under Texas Surface Water Quality Standards. All that was required was adhering to the equations and procedures in TCEQ assessment guidance (TCEQ, 2012).

Before applying the methods outlined above, the irregularities in the data must be addressed. For the missing data, an imputation algorithm was implemented using the '*mice'* package in R (van Buuren and Groothuis-Oudshoorn, 2011). To manage the multiply-censored data, two approaches were utilized. The first approach was to preserve the structure of the data by using non-parametric statistics. The second approach was to transform the multiply-censored data into a normally distributed data set. A short discussion of these techniques will be presented, followed by the analysis of the data to meet the stated objectives.

Missing Data Analysis

Typically, missing data become problematic in multivariate data sets. For example, consider an entry with measurements for ammonia and nitrate, but missing data on total phosphorus. There are two basic approaches for addressing the missing data. The first approach, called listwise deletion, simply deletes from the analysis any entries with at least one missing data point from the three parameters. However, this introduces bias in the analysis if a pattern to the missing data exists. Another method, denoted multiple imputation, uses mathematical relationships among the variables to fill in (or impute) the missing values. In this case, it is important that at least one of the parameters has no missing values. The parameters conductivity, DO, pH, temperature, and TOC all contained measurements for every sample collection date, and served in this analysis to generate complete data sets from the existing data sets containing missing values. The '*mice'* package generated 10 possible complete data sets. Each of these data sets can then be utilized for future statistical analysis. The missing values constituted less than 10% for each of the data sets.

Censored Data

The data sets for ammonia, COD, total phosphorus, TSS, and VSS all contained measurements above and below the detection limits. Measurements below the detection limits were marked with a "<". Parametric analyses cannot be conducted because the "<" measurements are not quantified. Often times, analysts will substitute values, such as 0 or the reporting limit, for the "<" sign. However, Helsel has shown that this also introduces bias to the analysis (2005). Therefore, either non-parametric analyses must be conducted on the data or the data must be transformed to make parametric analysis possible. For the non-parametric case, the analysis consists of ranking the measurements. Information is lost for the uncensored values, but the censored measurements are appropriately included in the analysis. For the parametric case, the censored data is transformed by regressing the order of the censored data along a normal distribution. It is assumed, however, that the uncensored data are normally distributed. This provides greater power for multiply-censored data, but can give false results for data sets when over 50% of data is censored. Done appropriately, either approach is valid and has been utilized in environmental statistics (Helsel, 2005). This report will utilize both approaches in analyzing the data with the anticipation that the results will be corroborating.

Results

ANOVA / MANOVA

The first objective of this report is to examine the impacts of the wastewater discharge as a function of distance. Oftentimes, it is sensible to conduct several analyses on the data in order to validate the conclusions. Thus, for this objective, two analyses were performed on the data. The first analysis, which assumed no correlations between the water quality parameters, utilized Analysis of Variation (ANOVA). For the second analysis, the impacts were examined using Multivariate Analysis of Variance (MANOVA). This analysis assumed the possibility of correlation between the parameters. Thus, MANOVA addresses questions on the comparison of a multivariate population and rests on the assumption of a multivariate normal population. However, since it is not clear whether this population comes from a multivariate normal distribution, the un-transformed data was analyzed using a Non-Parametric MANOVA, and the transformed data was analyzed using the conventional (parametric) MANOVA.

A “box and whiskers” chart of both the transformed and untransformed data is included in Appendix A. This chart shows the measurements across all the parameters. Looking at the chart, one immediately sees pronounced differences among locations for ions and nutrient parameters, such as chloride, nitrate, sulfate, and total phosphorus, as well as conductivity. Differences among the remaining parameters, such as TSS and TOC, were less clear. These differences were clarified after the statistical analyses were performed.

ANOVA

To determine a preliminary analysis of differences between sites, a parametric ANOVA was conducted on each of the ten normally distributed water quality parameters. The remaining five water quality parameters contained multiply-censored data, which were analyzed using the parametric and non-parametric approach. The non-parametric Kruskal Wallis ANOVA Test by Ranks, was performed for the untransformed data and the parametric ANOVA was performed on the transformed data. A comparison of the results between the non-parametric and parametric tests showed agreement in detecting significant differences among the locations validating the results from these tests.

Based on these results, COD, temperature, TOC, and VSS showed no significant differences between locations. Table 3 below indicates whether the differences were significant and the resulting p-values. A p-value below 0.33% for each parameter was used to indicate significant differences among locations. This threshold was based on the multiple comparison problem, which occurs when multiple evaluations are required. In this case, fifteen water quality parameters were evaluated separately to determine whether each parameter showed differences between locations. However, for each of these fifteen parameters, there exists a probability, called the p-value, for mistakenly declaring the differences significant where no such difference exists. It can be shown that the overall probability of making an error on at least one of the fifteen evaluations is larger than the individual parameter error rates. Thus, to account for this overall error, the Bonferroni approximation can be used. This adjustment is computed by taking the desired overall simultaneous error rate (5%) and dividing by the number of evaluations (15). To detect significant differences among the locations at a 5% error rate, each parameter should have a p-value of less than 0.33% (5% / 15 parameters). Tables of the means and confidence intervals of the means for each of the water quality parameters are presented in Appendix B.

Table 3: Results from Parametric and Non-Parametric ANOVA tests

	Parametric ANOVA Test		**Non-Parametric Kruskal_Wallis Test**	
	Significant Difference	p-value	Significant Difference	p-value
Ammonia[1]	Yes	<0.001	Yes	0.016
Chloride	Yes	<0.001	-	-
COD[1]	No	0.015	No	0.098
Conductivity	Yes	<0.001	-	-
DO	Yes	<0.001	-	-
***E. coli*[2]**	Yes	<0.001	-	-
Nitrate	Yes	<0.001	-	-
pH	Yes	<0.001	-	-
Sulfate	Yes	<0.001	-	-
Temperature	No	0.95	-	-
TDS	Yes	<0.001	-	-
TOC	No	0.105	-	-
Phosphorus[1]	Yes	<0.001	Yes	<0.001
TSS[1]	Yes	<0.001	Yes	<0.001
VSS[1]	No	0.14	No	0.45

1. Multiply-censored data sets required two tests, a parametric test on the transformed data set and a non-parametric test. Non-censored data sets did not require the non-parametric test.
2. Data on E.Coli required a fourth-root transformation in order to maintain assumptions in ANOVA.

While the Bonferroni approximation is convenient at providing rough estimates of the differences between sites, it is typically used when the evaluations are considered independent of each other. However, each of the water quality parameters is not independent and has some level of correlation with another parameter. When these correlations are present, a more appropriate determination of the overall effect of the water quality parameters is to use a multivariate approach.

MANOVA

A matrix of the correlation between the fifteen parameters is included in Appendix D. This matrix shows some level of correlation among the parameters, as well as among conductivity and the nutrients. Given these correlations, it is prudent to consider whether these interactions will still indicate significant differences in location. In a more mathematical sense, the question involves comparing the vector of parameter means at each of the five sample sites. The Multivariate Analysis of Variance (MANOVA) is well suited to this question. However, to implement MANOVA, the transformed (rank) data should be utilized to avoid the irregularities of the missing and censored data. The results from the MANOVA on the transformed data set (Table 4) show the same outcome as the ANOVA. That is, a significant difference exists among the locations as depicted by a "p-value" (i.e. the "Pr(F)" term in the table) value less than 2.2e-16.

Table 4: MANOVA Table for Comparing Parameter Mean Vectors

	Df	Pillai approx	F num	Pr(>F)
MArea	4	0.89414	11.577	< 2.2e-16 ***
Residuals	573			

To test whether the transformed data misrepresents the sample results, a non-parametric version of MANOVA was conducted. This version is based on work published by Anderson (2001) and was performed with the R program's *'vegan'* package (Oksanen et al., 2013). Results from the Non-Parametric MANOVA also show a significant difference between locations (Table 5).

Table 5: Non-parametric MANOVA Table for Comparing Parameter Mean Vectors

	Df	Wilks approx	F num	Pr(>F)
MArea	4	0.36283	11.594	< 2.2e-16 ***
Residuals	573			

While it is reassuring to see that three different statistical tests lead to the same conclusion (i.e., significant differences between the locations), it is useful to see which locations differed from the others. To do this, Tukey's Honest Significant Difference (HSD) test was utilized. For this post-hoc analysis, most of the differences were identified to occur between sampling stations Areas 43 and/or 44 and sampling stations further downstream (Areas 45, 47 and/or 48). This surprisingly indicates that even though Area 44 is downstream of the Walnut Creek Wastewater Treatment Facility, it has water quality parameters characteristics similar to the sampled site upstream of the Facility, Area 43. This may be due to the result of insufficient mixing of the nutrients throughout the cross-sectional area of the stream. That is, the effluent was discharged at a point and produced a plume of nutrients which was not directly sampled. However, by the time the plume arrives at Area 45, the nutrients have been well mixed throughout the river.

Area 48, which is over two miles from the South Austin Regional Wastewater Treatment Facility, still retains similar water quality parameter characteristics of sampled sites closer to the treatment facility. This might indicate the lack of recovery of the Colorado River from wastewater discharge. Concentrations of *E. coli* were higher in the upstream locations than downstream locations.

Vector AutoRegression Models

The second objective of this report is to examine the data temporally. The choice of Vector AutoRegression Models was motivated, in part, by the findings of a previous report conducted by the City of Austin (1986). The rationale derived from the City of Austin (1986) report is explained below followed by the results from the Vector AutoRegression (VAR) model.

Previous Wastewater Effluent Data and Analysis

The City of Austin (1986) prepared an analysis on the water quality for the Colorado River, similar in scope to the one conducted in this report. The results from the City of Austin (1986) analysis showed similar findings to those presented here. For example, among the conclusions, the City of Austin (1986) report stated:

> In general, the water quality at the FM973 sampling site is significantly different from that of upstream stations. The concentrations for BOD, NO_3, NH_3, TKN, and TP are significantly higher due to discharge of treated sewage entering the Colorado River above this sampling site.
>
> Along the river between Mansfield Dam and the Hwy 183 sampling site, there is no significant spatial variation in concentration among sampling sites for most water quality parameters.

The first quote refers to the sampling site closest to Area 45, which was shown to be higher in concentrations in this report than that of upstream stations. The second quote, which referred to Areas 43 and 44 in this report, verifies the results from this report showing that concentrations of most water quality parameters are low in upstream locations.

However, the City of Austin (1986) report differs from this report in some findings such as:

> Data for water quality constituent concentrations, when transformed to logarithm, are normally distributed. This implies that the normal distribution regression and correlation models can be formulated for trend analysis

From this result, the analysis follows with:

> There are significant increasing time trends for TKN at the Highway 183 (Hwy 183) site, and for NO_3 at Farm Road 973 (FM 973).

Thus, as far back as 1986, significant temporal trends were found by transforming the data using the natural logarithm. There are generally two reasons for transforming data. First, linear regression models require the assumption of normally distributed and constant errors between the model and the data. Thus, if a plot of the errors (also called residuals) show non-constant errors, then a transformation can be utilized to maintain constant errors throughout the domain of the independent variable. A second reason is that if the underlying phenomenon is non-linear, then transforming the data into a linear function can be used to simplify the model. In either case, it is the residuals, not the response (the raw data), that should be tested or transformed for normality. This was one point in which the City of Austin (1986) report was in error as it only considered the normality of the transformed data.

Since there is no mention of residuals in the City of Austin (1986) report, we assumed that the report treated the underlying relation between constituents and time as non-linear. This relation is fundamentally non-linear; however, the 1986 report again errs by specifying the relation to be an exponential model (since the transformation is based on the natural logarithm). This can be seen by looking at the plot taken from the report and shown in Figure 3 below.

Figure 4 shows the nitrate (NO_3) results from samples collected at FM 973 denoted with an "A"[1]. The data is plotted on a natural logarithm scale on the y-axis, which can be confirmed by seeing that the number in parentheses along the y-axis is just the exponential of the non-parenthetic numbers (that is, $e^1 = 2.72$; $e^{0.5} = 1.65$; $e^{0.0} = 1.00$; and so on). The points denoted by a "P" indicate the predicted or model values and the "U" and "L" points represent the upper and lower limits of the confidence interval for the model, respectively.

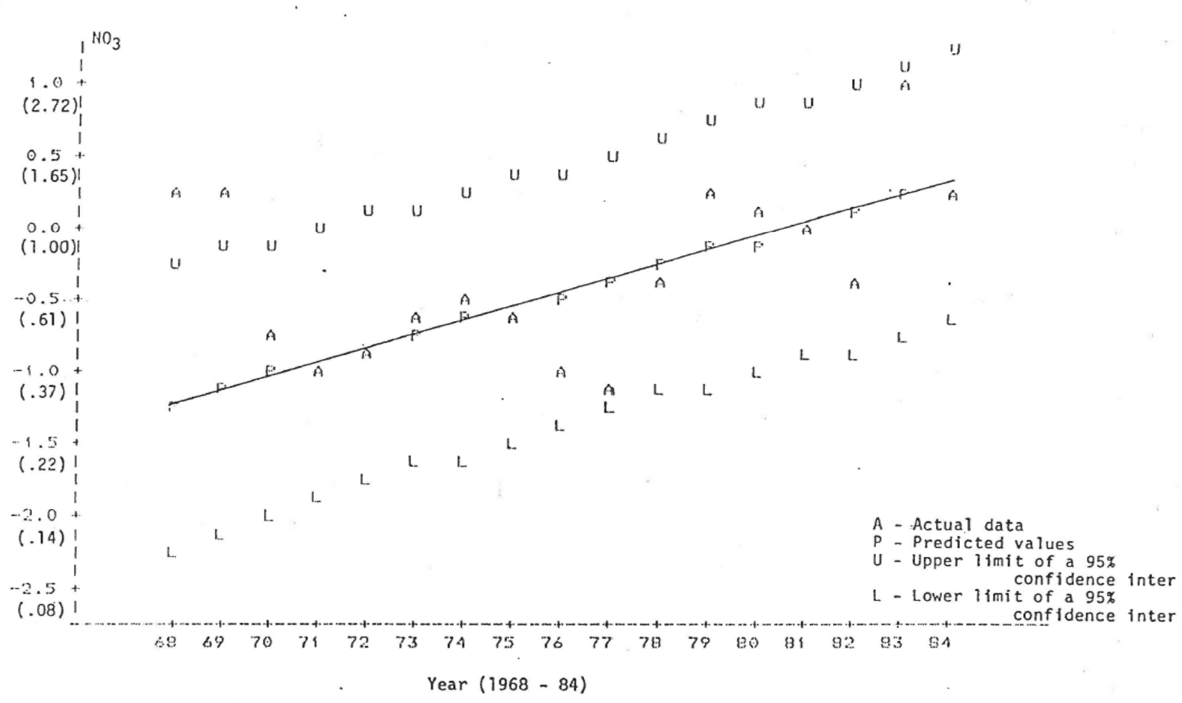

Figure 2. Trend Analysis for NO_3 Concentration Data for Colorado River at FM 973

Figure 4: Re-printed Plot of Trend Analysis of Nitrate Data

Based on the positive slope of this model, the 1986 report concludes that the temporal trend of the model is significant. Given that almost twenty years has passed since the publication of this report, this model can be tested by extrapolating it into the future. Figure 5 below shows the

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[1] The results are actually the geometric means of the samples collected during that respective year. Taking the geometric mean is an odd choice for combining data that can be considered to be additive. However, this report will continue with that choice.

same plot but with the confidence intervals extended through 2012 and the current 2002 through 2012 data appended to it.

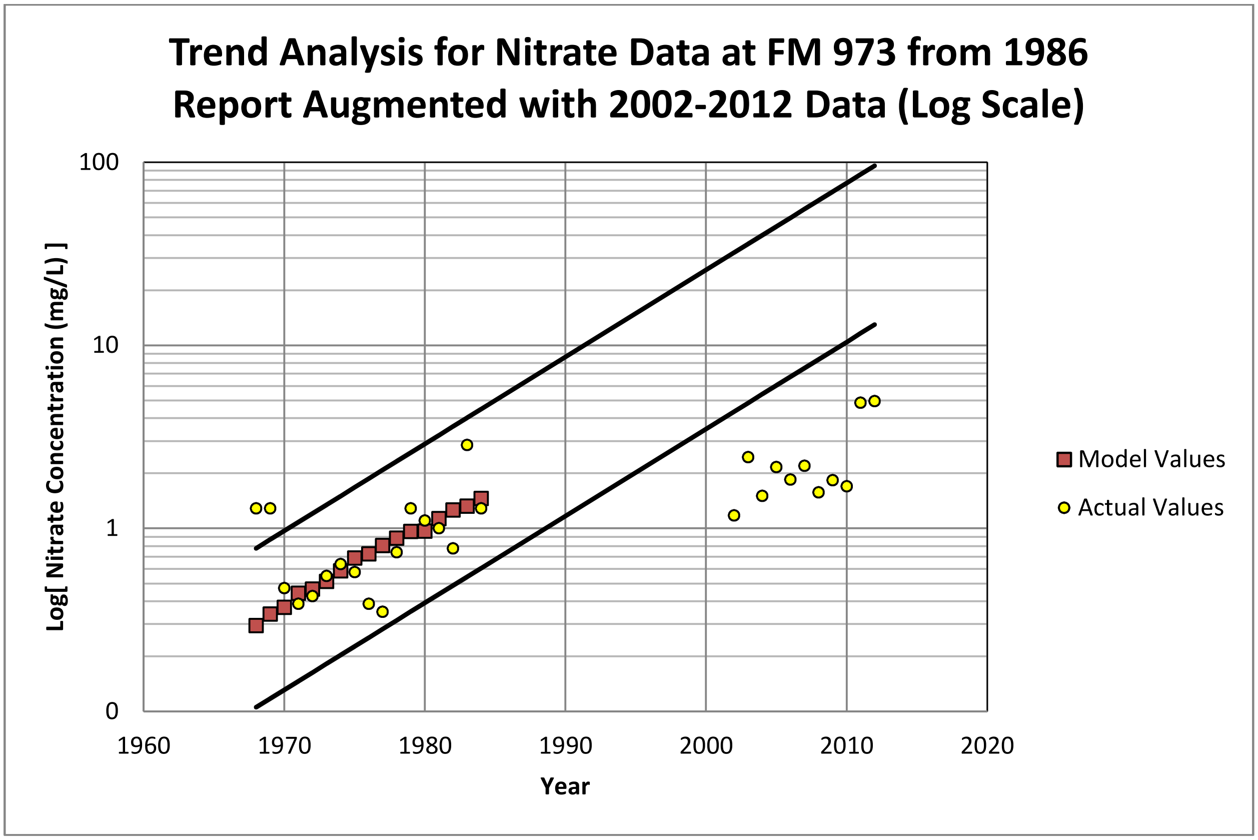

Figure 5: Trend Analysis of Nitrate Data from 1986 and Current Data

The plot clearly shows that all of the current data is well below the confidence intervals. While this may seem to be an encouraging sign, upon closer look, it is actually an indication of problems with the model. These problems can be explained by seeing the next plot, Figure 6 below, which shows the same plot but with the y-axis under a non-logarithmic scale.

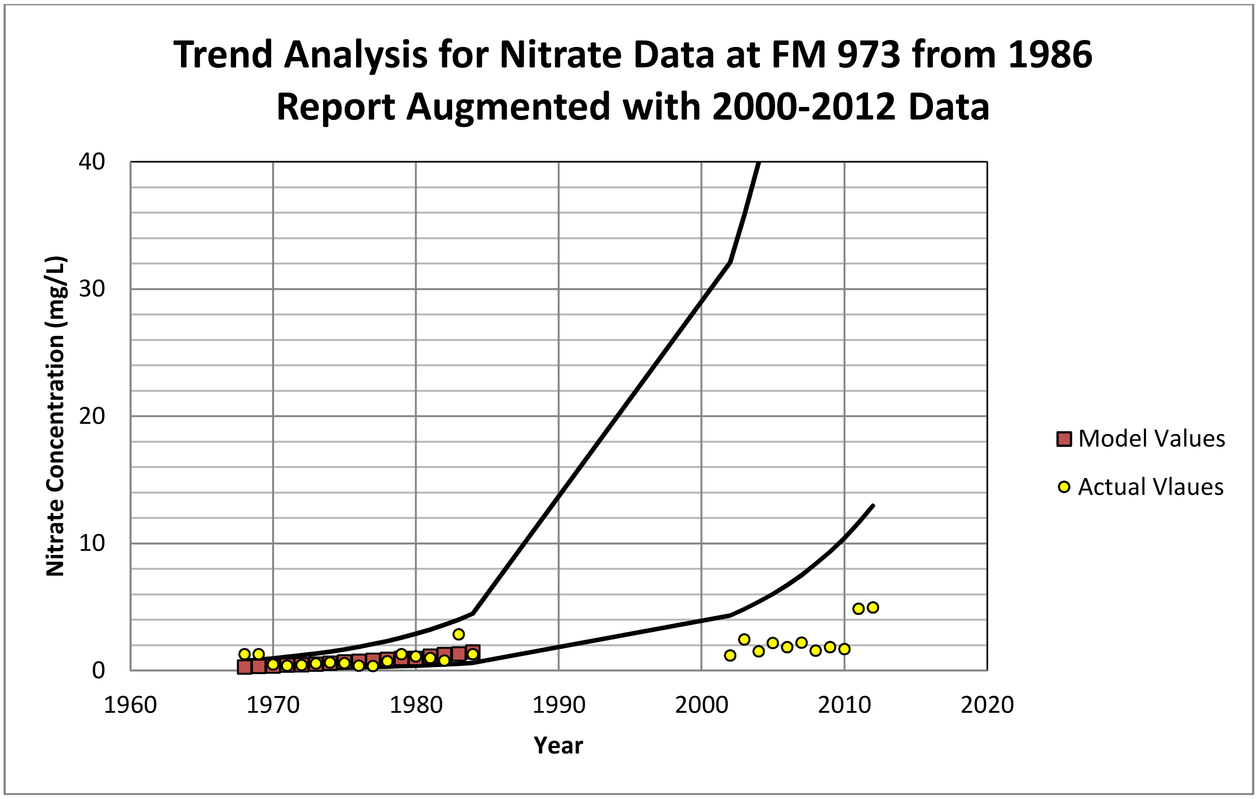

Figure 6: Trend Analysis of Nitrate Data from 1986 and Current Data (Untransformed)

By looking at this model in the untransformed state, the problem of proposing an exponential model can be clearly seen. Had the data from 2000-2012 fallen within the confidence intervals of the model, this would have verified the exponential growth of nitrate at FM 973. Fortunately, exponential growth did not occur; however, this shows that caution (or at least, more data) is needed when positing exponential models. The other lesson is that while logarithms are necessary tools for examining non-linear models, they should not be used in every case for the sole purpose of fitting the data to a normal distribution. In this case, the transformation scaled down the measurements in order to meet the normally distributed error assumption and a trend was identified. However, when that model is converted back to the original units, the trend becomes exaggerated and unrealistic.

Even without assuming an exponential model, there does not appear to be a temporal trend in the geometric means of the nitrate data. A linear regression model was conducted on the data from both the City of Austin (1986) report and the current 2002-2012 data (Figure 7 below). Interestingly, both sets of data had a positive slope of 0.051 mg/L. This would indicate that the annual geometric mean of nitrate tends to go up about 0.051 mg/L every year; however, based on the sample size of 28, there was not enough data to distinguish that slope from a zero slope. Thus, there was no evidence of a temporal trend in the geometric means of nitrate starting from 1968. It is entirely possible that taking the geometric means of the data is masking the true trends, but in light of all of this information, it appears that a more sophisticated approach to finding temporal trends using Vector AutoRegression (VAR) is warranted.

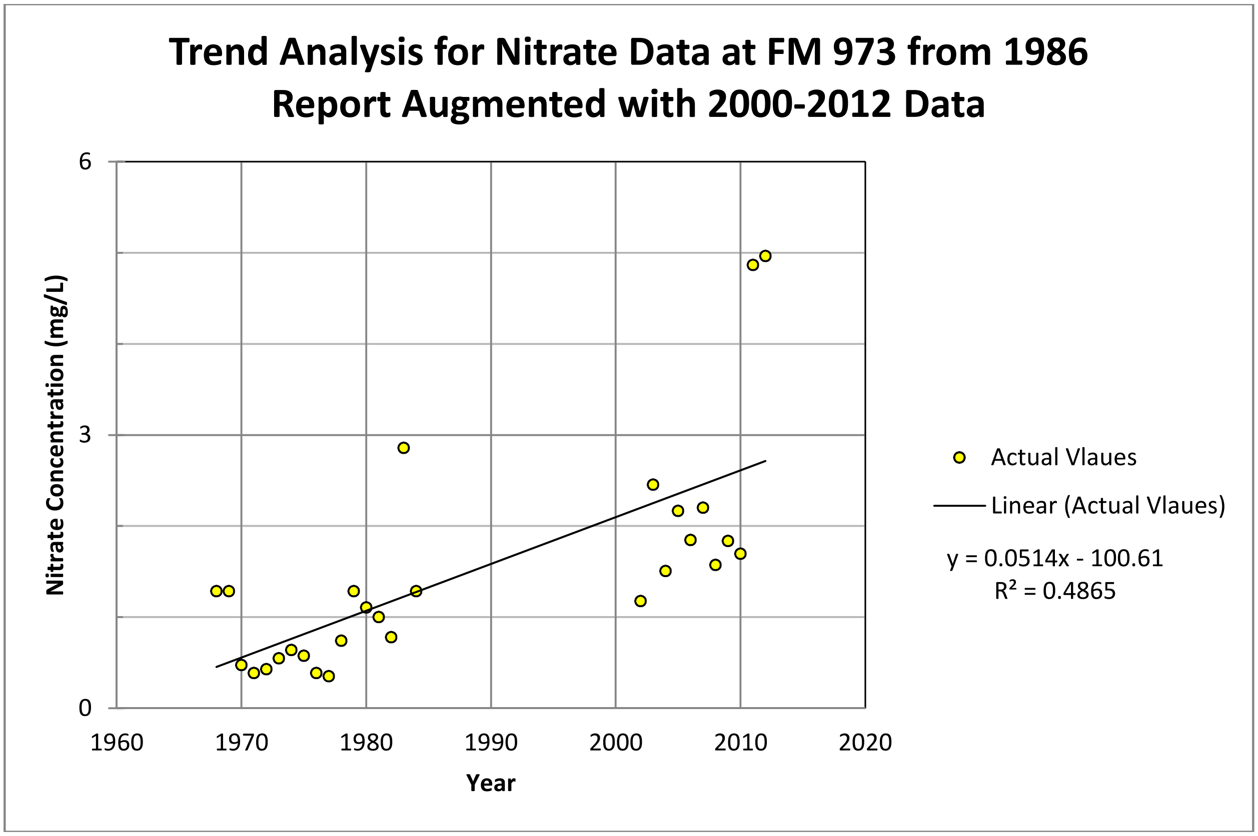

Figure 7: Trend Analysis of Nitrate Data from 1986 and Current Data

<u>Vector AutoRegression Models</u>

The previous critique of the City of Austin (1986) report showed that, at this time, regressing the results against time led to inconclusive outcomes. Therefore, a used Vector AutoRegression (VAR), to improve our confidence in whether temporal trends could be found or not. This analysis is a natural extension of time series analysis. However, when applied to the data, this analysis was complicated by the presence of censored data. Unlike the spatial data, in which measurements at each location could be ordered arbitrarily, for time series data at each location, order matters. Furthermore, determining autocorrelations for censored data is difficult. While using non-parametric correlations to inform the autocorrelation is logical, the literature in this area of statistics is scarce. Because of this and the complexity of VAR, the analysis was only conducted on water quality parameters where the data set has no censored values. The fully uncensored data set exists for chloride, conductivity, DO, *E. coli*, nitrate, pH, and TOC in all locations.

Additionally, because flow has the potential for impact on parameter concentration, it was included in the analysis. Given a correlation between flow and each of the above parameters, the analysis should account for this multivariate time series. Thus, the VAR Model examined the behavior between flow and each of the parameters.

The outputs from the VAR model are parameter estimates, θ_{ij}, for the coupled time series of the form:

$$Q_t = \sum_{i=1}^{j} \theta_{1i} Q_{t-j} + \sum_{m=j+1}^{j+k} \theta_{1j} x_{t-m-j} + w_{x,t} \tag{1a}$$

$$x_t = \sum_{i=1}^{j} \theta_{2i} Q_{t-j} + \sum_{m=j+1}^{j+k} \theta_{2j} x_{t-m-j} + w_{Q,t} \tag{1b}$$

In this equation, Q_t and x_t are the time series for flow and the water quality parameter, respectively, at time *t*. The terms *j* and *k* are the time series orders for flow and the water quality parameters, respectively, and $w_{Q,t}$ and $w_{x,t}$ are the white noise time series for flow and the water quality parameters, respectively.

Thus, a VAR process of order 1 would follow:

$$Q_t = \theta_{11}Q_{t-1} + \theta_{12}x_{t-1} + w_{Q,t} \tag{2a}$$

$$x_t = \theta_{21}Q_{t-1} + \theta_{22}x_{t-1} + w_{x,t} \tag{2b}$$

A VAR process of order 2 would follow:

$$Q_t = \theta_{11}Q_{t-1} + \theta_{12}Q_{t-2} + \theta_{13}x_{t-1} + \theta_{14}x_{t-2} + w_{Q,t} \tag{3a}$$

$$x_t = \theta_{21}Q_{t-1} + \theta_{22}Q_{t-2} + \theta_{23}x_{t-1} + \theta_{24}x_{t-2} + w_{x,t} \tag{3b}$$

This pattern can continue until the parameters θ_{ij} are no longer significant. Since this report is concerned with characterizing and predicting the parameter value rather than the flow, only the results from Equation 1b will be shown.

The R package *'vars'* was used to implement the VAR model and determine the appropriate time series order (Pfaff, 2008). As an example, parameter estimates for the nitrate time series are shown in Table 6 below. The *'vars'* package indicated that a multivariate time series for Area 43 would be best fit with a VAR process of order 1, while a multivariate time series for Area 44 should follow a VAR process of order 2. Tests indicating significance of the parameter estimates are shown in bold. Note that if the flow parameter estimates are not significant (as is the case for Areas 43, 44, 45, and 47), then the result reduces to a univariate time series.

Table 6: VAR Parameter Estimates for Nitrate

Area	θ_{21} (Flow$_{t-1}$)	θ_{22} (Flow$_{t-2}$)	θ_{23} (Nitrate$_{t-1}$)	θ_{24}(Nitrate$_{t-2}$)
43	1.46E-05		**0.437**	
44	3.99E-06	7.42E-06	**0.479**	**0.357**
45	8.26E-05		**0.637**	
47	-4.26E-05	3.97E-05	**0.701**	-0.0389
48	**-2.07E-04**	6.53E-05	**0.628**	0.0549

Inserting the values for Area 43 into Equation 2b provides an example of the VAR resulting in a univariate time series. Thus, the parameter nitrate can be characterized by:

$$x_t = 0.437 \cdot x_{t-1} + w_{x,t}$$

This shows that the current value for nitrate at Area 43 can be estimated from the previous month's value nitrate. The same could be done for Area 44, which has an order of 2:

$$x_t = 0.479 \cdot x_{t-1} + 0.357 \cdot x_{t-2} + w_{x,t}$$

This equation shows that the current value for nitrate at Area 44 is dependent on the previous two month's values nitrate. The estimates for Area 48 give the only bivariate results for nitrate. This relation is expressed as follows:

$$x_t = -0.000207 \cdot Q_{t-1} + 0.628 \cdot x_{t-1} + w_{x,t}$$

Area 48 had a significant negative temporal relation to flow, (i.e., as flow from the previous month increases, the nitrate concentration decreases). These parameters and equations can also be used to predict nitrate values into the future by inserting current values of flow and nitrate into the *t-1* term. However, because the estimate parameters (θ_{ij}) are random variables, the standard errors are needed in order to bound the estimates and the parameters.

Tables 7 and 8 below shows the standard errors and resulting confidence intervals forecast three months from the last data point obtained for nitrate for this report. Flow from March through May of 2013 (which was measured as 124.7 cfs, 397.8 cfs, and 508 cfs, respectively) was used in this determination. These flows, when compared to those on the histogram in Figure 3, show much lower flows than average flows for the summer months. Thus, based on the VAR equations for Areas 43 through 48, one would expect higher than average concentrations for nitrate in Areas 48.

Table 7: VAR Estimates of the Standard Errors for Nitrate (mg/L)

Area	θ_{21}	θ_{22}	θ_{23}	θ_{24}
43	1.60E-05		8.45E-02	
44	1.71E-05	1.69E-05	8.97E-02	9.08E-02
45	9.39E-05		7.78E-02	
47	1.23E-04	1.23E-04	9.69E-02	9.81E-02
48	1.07E-04	1.06E-04	9.79E-02	8.90E-02

Table 8: VAR Forecasts for Nitrate (mg/L)

Area	March 2013			April 2013			May 2013		
	Lower	Forecast	Upper	Lower	Forecast	Upper	Lower	Forecast	Upper
43	0.11	0.14	0.17	0.05	0.06	0.08	0.02	0.03	0.05
44	0.20	0.26	0.32	0.17	0.22	0.27	0.15	0.20	0.25
45	3.50	4.00	4.50	2.24	2.56	2.88	1.43	1.66	1.90
47	5.18	7.14	9.11	2.82	4.59	6.36	1.72	2.93	4.14
48	4.49	6.39	8.30	3.03	4.50	5.98	2.04	3.10	4.17

In fact, the nitrate lower bound forecasts for March in Areas 45, 47, and 48 (3.50 mg/L, 5.18 mg/L, and 4.49 mg/L, respectively) are all higher than the upper confidence intervals of their respective means (3.4 mg/L, 4.4 mg/L, and 4.1 mg/L, respectively). Table 9 below reproduces the estimates of the mean and confidence intervals of the mean from Appendix B, which was obtained from the previous ANOVA results. This indicates that above average concentrations were forecasted for nitrate in Areas 45, 47, and 48. However, as the flow increased in April and May 2013, the concentrations, while still high relative to Areas 43 and 44, decreased from the previous months.

Table 9: Confidence Intervals and Mean Concentrations for Nitrate

Area	2.5%-ile	Mean	97.5%-ile
43	<0.05	0.3	0.7
44	0.1	0.5	0.9
45	2.6	3.0	3.4
47	3.6	4.0	4.4
48	3.3	3.7	4.1

The complete set of parameter estimates, standard errors, and predictions is included in Appendix C. Chloride and nitrate were the only parameters which predicted forecasts of concentrations higher than the upper confidence interval of the mean. Thus, flow had a non-significant effect on the remaining parameters.

While this analysis does not test for temporal trends, it can be useful for comparing future measurements with the forecasts. For example, if future flows continue to remain at low stages, then it is expected that concentrations will become greater than the mean. If the future measurements fall above the upper forecast, then that might indicate an increase the water quality parameter that is not accounted for by decreases in the flow.

E. coli data require a fourth root transformation. The parameter estimates of the VAR for *E. coli*, thus, apply to the transformed data. Results from the *E. coli* time series equation using these estimates, however, require a transformation back to the original units by raising the result to the fourth power.

Compliance with Sections 305(b) and 303(d) of the Federal Clean Water Act

The final objective of this report is to determine whether the sampled sections of the Colorado River would be compliance with Sections 305(b) and 303(d) of the Federal Clean Water Act as implemented by the TCEQ if sampling complied with CRP specifications. Standards on the individual river sections are set by TCEQ, and the water quality criteria for individual constituents in the segment of the Colorado River below Lady Bird Lake are outlined in 30 Texas Administrative Code (TAC) §307.7. The:

- The average of the samples for the past seven years must be below:
  100 mg/L for cloride (Cl^{-1});
  100 mg/L for sulfate (SO_4^{-2});
  500 mg/L for TDS; and
  95°F for temperature.

- The geometric mean of the samples must be below:
  126 colonies/100mL for *E. coli*

In determining impairment or concerns for stream segments, the number of times that the samples exceed the below criteria must be evaluated using the Binomial Method, as described in the 2012 Guidance for Assessing and Reporting Surface Water Quality in Texas (TCEQ, 2012):

1.95 mg/L for nitrate-nitrogen;
0.33 mg/L for ammonia-nitrogen;
0.69 mg/L for total phosphorus;
6 mg/L for DO at stream flows greater than 150 ft^3/sec;
5 mg/L for DO at stream flows less than 150 ft^3/sec; and
6.5 to 9.0 range for pH.

The results for the parameters requiring averaged data are as follows.

Table 9: The Average of Measurements for the past Seven Years

Area	Cloride (Cl^{-1}) (mg/L)	Sulfate (SO_4^{-2}) (mg/L)	TDS (mg/L)	Temperature (°F)
43	32.1	29.8	294.8	70.6
44	32.5	29.2	291.2	69.8
45	43.6	48.5	349.7	70.2
47	47.7	48.6	346.3	70.2
48	45.8	46.9	339.6	70.3

Each of these sampling sites met the criteria for the parameters chloride, sulfate, TDS, and temperature. The results for the geometric mean of the *E. coli* samples are below, which also met the criteria.

Table 10: The Geometric Mean of *E. coli*

Area	*E. coli* (#/100mL)
43	75.6
44	33.5
45	27.3
47	46.7
48	51.5

To evaluate the third criteria in 30 TAC §307.8, the first step is to count the number of times that the sampled sites exceeded each of the parameter's criteria (TCEQ, 2012). Table 11 below shows these counts.

Table 11: Number of Times the Criteria Was Exceeded

Area	Nitrate-Nitrogen	Ammonia-Nitrogen	pH	Total Phosphorus	DO
43	1	0	1	0	7
44	0	1	0	0	12
45	56	1	0	22	11
47	76	3	7	50	8
48	69	0	1	44	12

Thus, 69 samples in Area 48 exceeded the nitrate-nitrogen criteria of 1.95 mg/L. To determine whether this complies with the guidance, the probability that proportion of exceedances did not occur more than 10% of the time should have a Type I error rate of less than 20%. This determination can be done with the Cumulative Binomial Distribution function, which gives the probability that the proportion of exceedances, p, given k or less exceedances for n trials (where $p < n$). Mathematically, this is expressed as:

$$\Pr ob(X > x) = 1 - \sum_{k=0}^{x} \binom{n}{k} p^k (1-p)^{n-k} \tag{4}$$

For nitrate-nitrogen, ammonia_nitrogen, pH, and total phosphorus, the TCEQ guidance indicates that the proportion of exceedances, p, is 0.10 or less for standards attainment. If the result of Equation 4 is greater than 20%, then that sampled site did not meet the standard and could be considered impaired. For DO, the exceedance proportion, p, is 0.08 with a Type I error rate of no more than 20%.

Based on this equation, the determination of whether the samples sites support designated uses are listed in the table below.

Table 12: Concerns under the Screening Levels of the Binomial Method

Area	Nitrate-Nitrogen	Ammonia-Nitrogen	pH	Total Phosphorus	DO
43	No	No	No	No	No
44	No	No	No	No	Yes
45	Yes	No	No	Yes	Yes
47	Yes	No	No	Yes	No
48	Yes	No	No	Yes	Yes

This table shows that nitrate-nitrogen, total phosphorus, and DO would not meet the standards for concern set by the State for the sampled sites downstream of the wastewater effluent discharge point.

Conclusion

Data taken from five locations along the Colorado River downstream of Longhorn Dam were analyzed for differences between location, trends in time, and for compliance with Texas Surface Water Quality standards. The two upper-most sample sites were up-gradient or adjacent to City of Austin wastewater treatment plant effluent discharge points. The lower three sampled sites were up to 2 miles below the discharge points. These sites were sampled for a suite of fifteen water quality parameters. Analysis to detect differences among locations showed significant degradation of the three downstream sites for each of the water quality parameters, except for VSS, TOC, and temperature.

Another analysis was performed to detect temporal trends in the water quality parameters. Traditional analyses regressing the parameter with time failed to detect whether significant trends were present or not. Instead, a more sophisticated statistical approach was taken that was a natural extension of time series analysis. This approach, called Vector AutoRegression (VAR), linked flow with some of the water quality parameters. Those parameters without a flow component were reduced to an autoregressive time series model. Those parameters with a significant flow component, chloride, conductivity, DO, nitrate, and TDS, showed that a decrease in flow accounted for some of the recent increase in water quality parameters. However, more testing of this approach is required.

A final analysis examined whether the sampled sites fully support designated uses and attainment of the water quality standards applicable to the Colorado River below Town Lake, and not be considered impaired or of concern under sections 303(d) or 305(b) of the Clean Water Act. The results showed that the downstream sites could be considered impaired for nitrate-nitrogen, total phosphorus, and DO. However, chloride, sulfate, TDS, and temperature would all meet the applicable standards.

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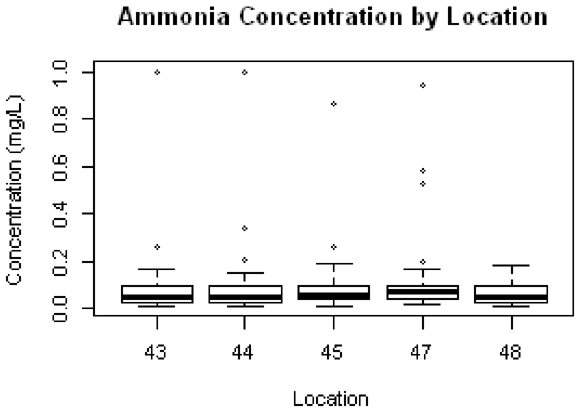
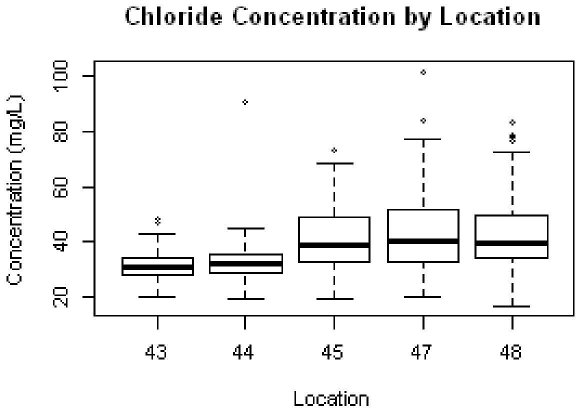
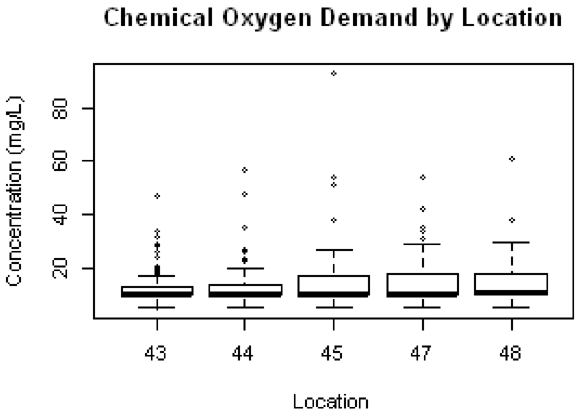
Appendix A

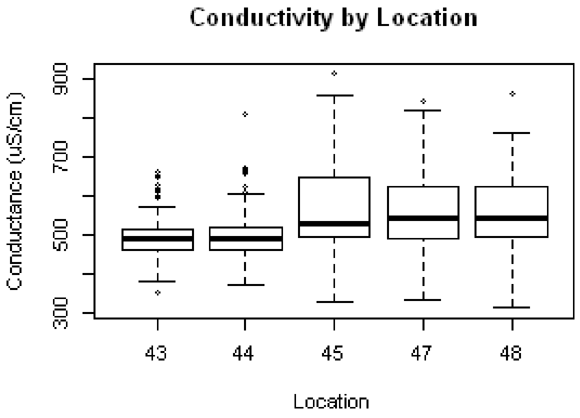
Plots of the Data under Transformed and Untransformed Conditions

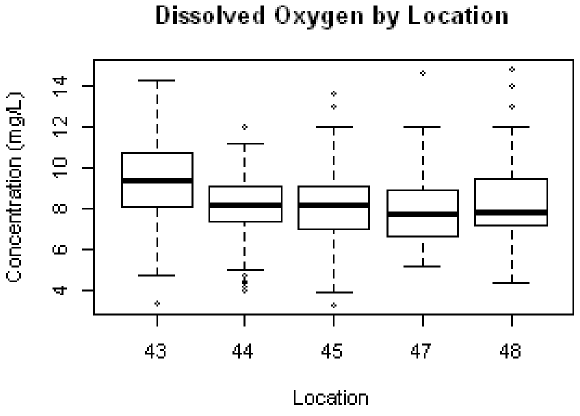
Raw Data

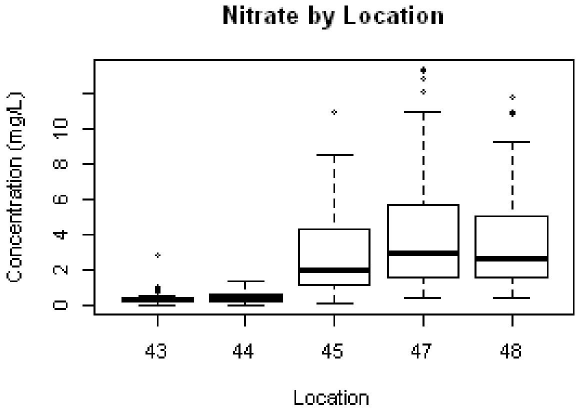

Ammonia Concentration by Location

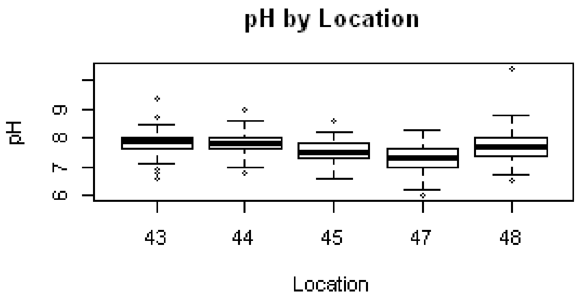

Chloride Concentration by Location

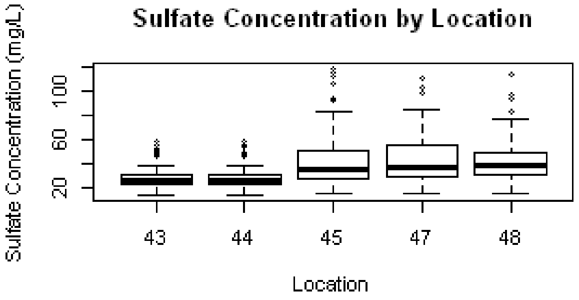

Chemical Oxygen Demand by Location

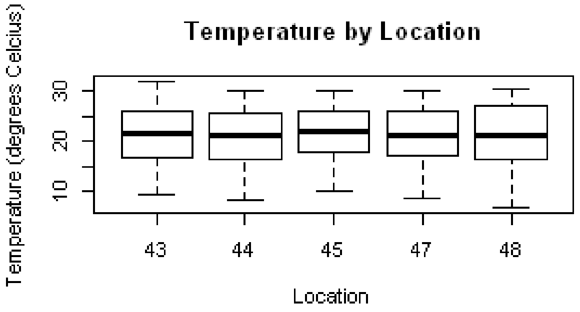

Conductivity by Location

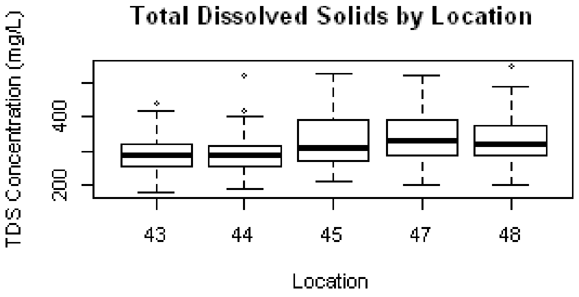

Dissolved Oxygen by Location

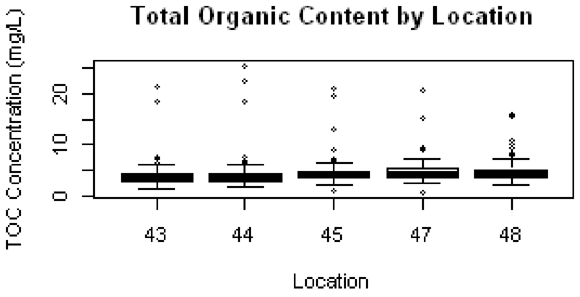

Nitrate by Location

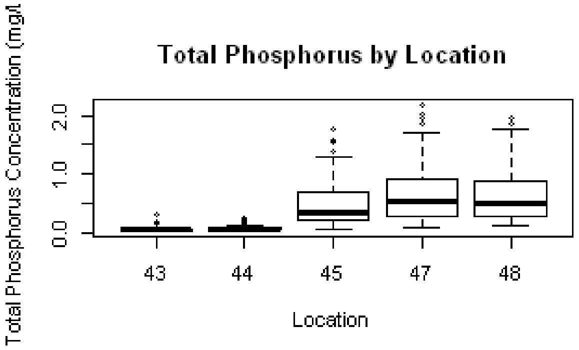

pH by Location

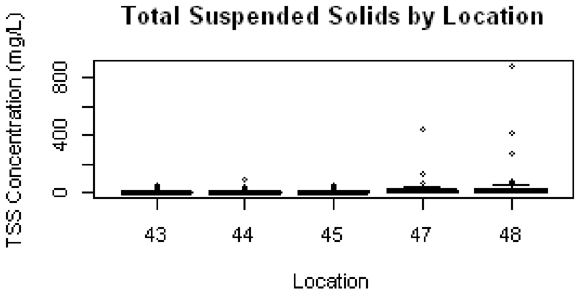

Sulfate Concentration by Location

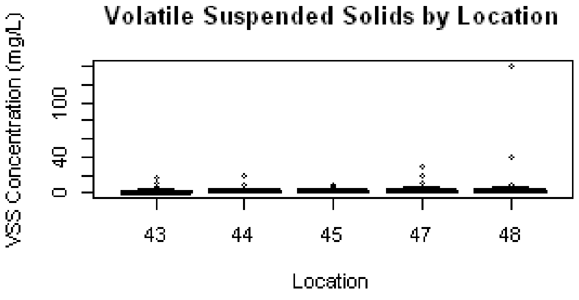

Temperature by Location

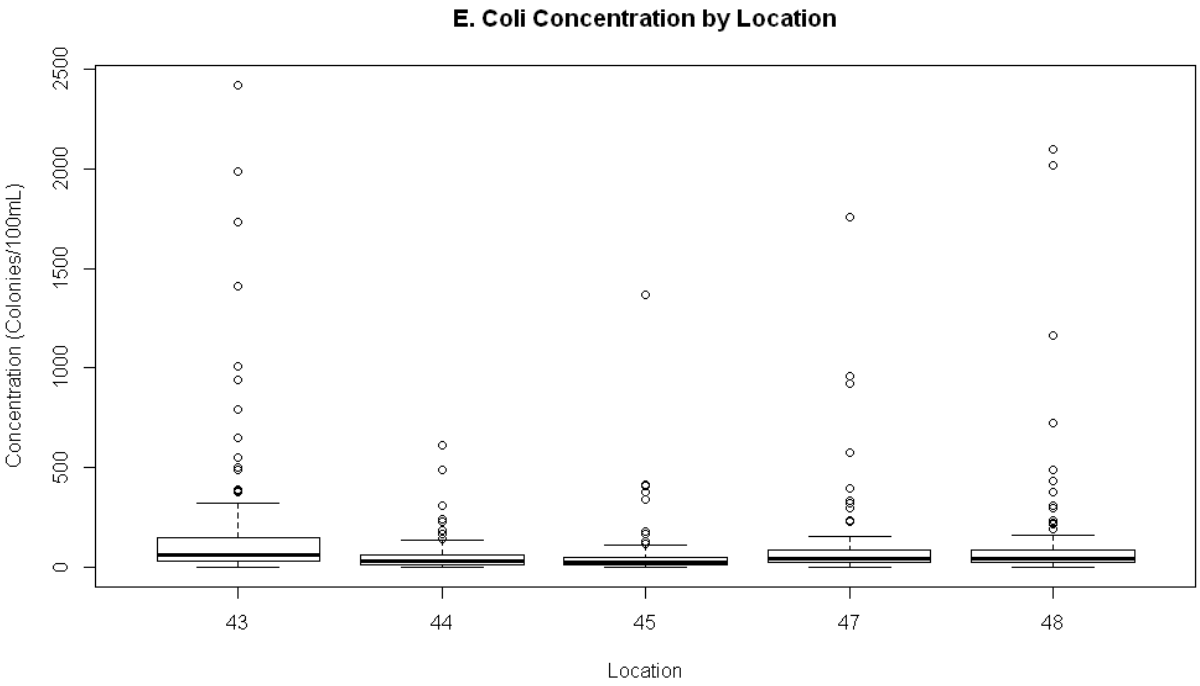

Total Dissolved Solids by Location


Total Organic Content by Location

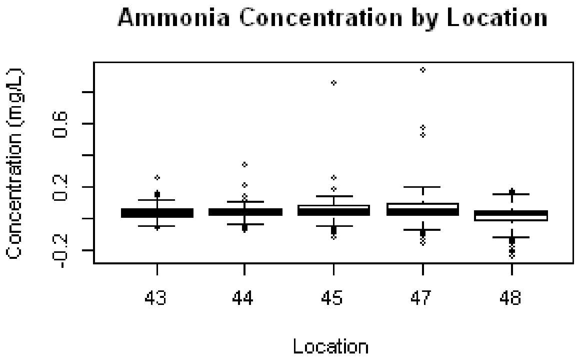

Total Phosphorus by Location

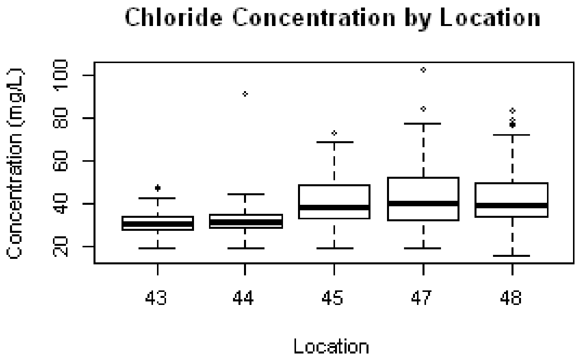

Total Suspended Solids by Location

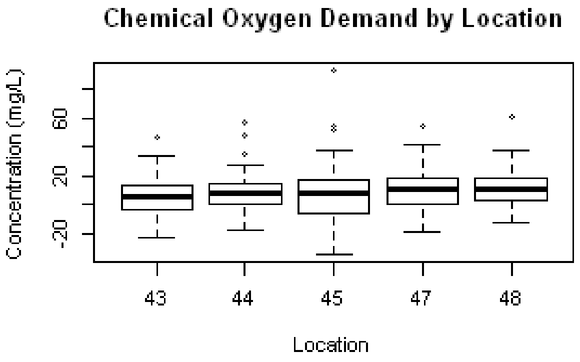

Volatile Suspended Solids by Location

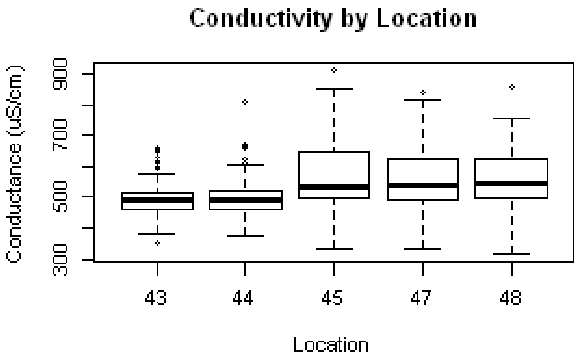

E. Coli Concentration by Location
Concentration (Colonies/100mL)
0
500
1000
1500
2000
2500
43
44
45
47
48
Location

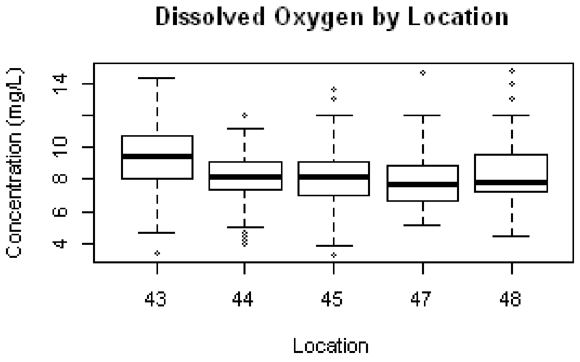
TRANSFORMED DATA

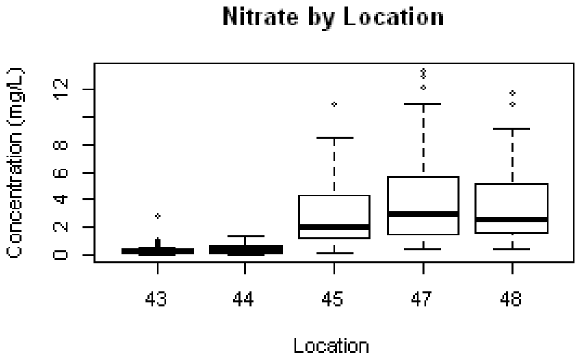

Ammonia Concentration by Location

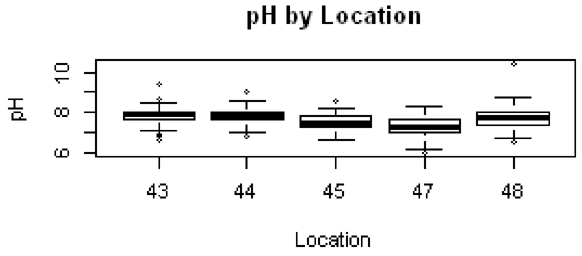

Chloride Concentration by Location

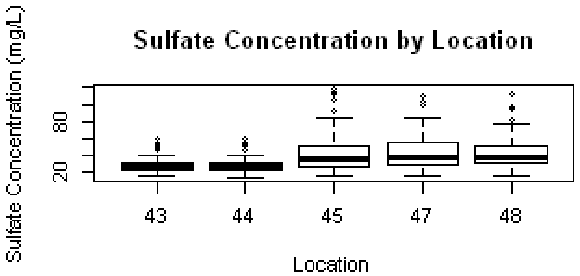

Chemical Oxygen Demand by Location

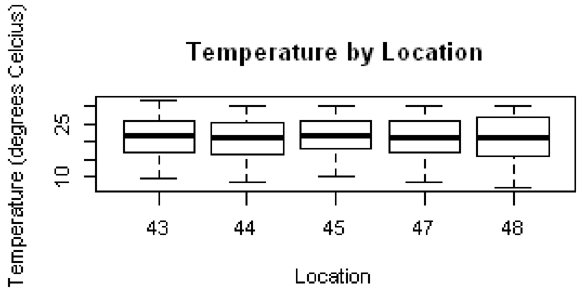

Conductivity by Location

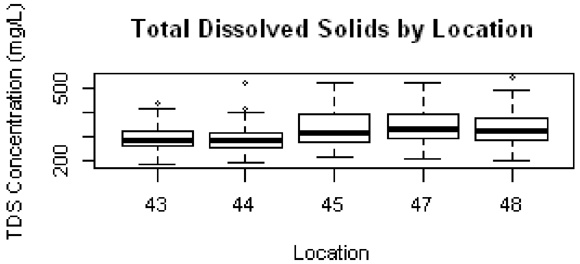

Dissolved Oxygen by Location

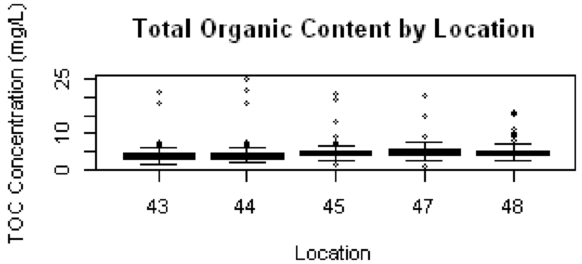

Nitrate by Location

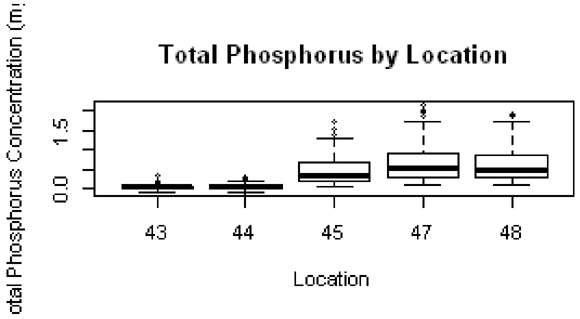

pH by Location

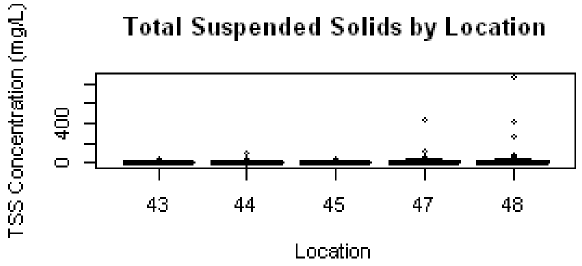

Sulfate Concentration by Location

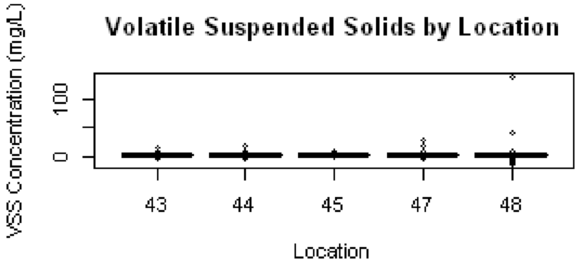

Temperature by Location

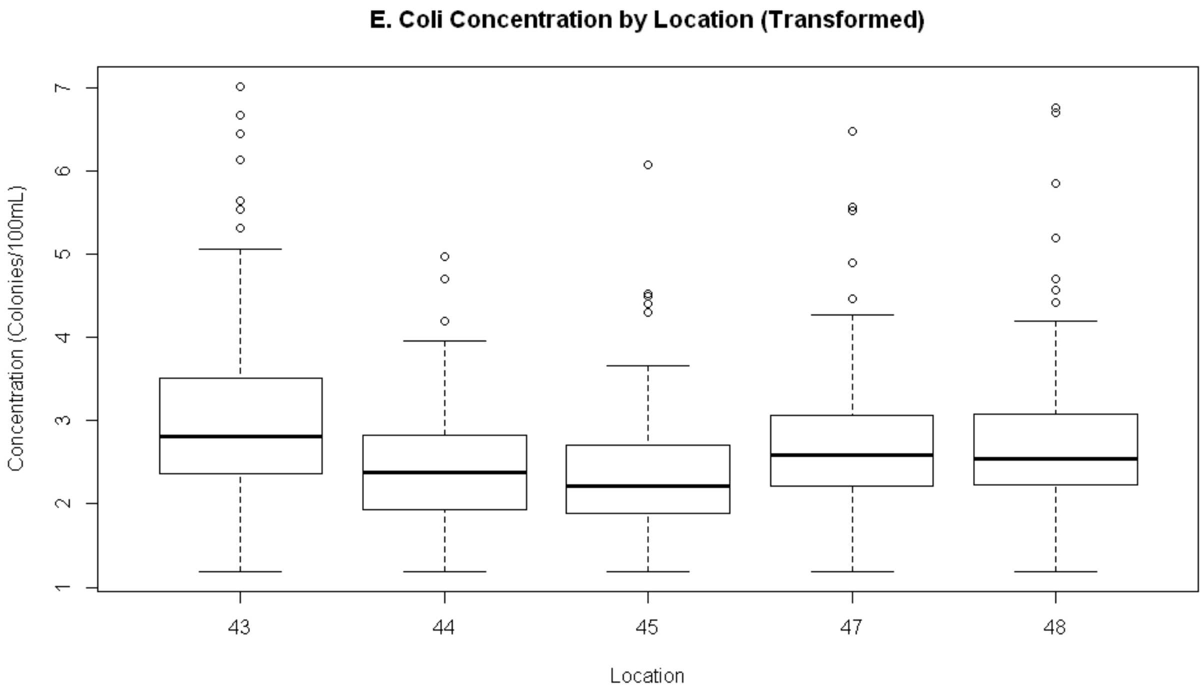

Total Dissolved Solids by Location


Total Organic Content by Location


Total Phosphorus by Location


Total Suspended Solids by Location


Volatile Suspended Solids by Location



E. Coli Concentration by Location (Transformed)
Concentration (Colonies/100mL)
1
2
3
4
5
6
7
43
44
45
47
48
Location

Appendix B
Table of Estimates of the Mean of Each Parameter

Ammonia

Area	2.5%-ile	Mean	97.5%-ile
43	<0.1	<0.1	<0.1
44	<0.1	<0.1	<0.1
45	<0.1	<0.1	<0.1
47	<0.1	<0.1	<0.1
48	<0.1	<0.1	<0.1

Note: Ammonia had an upper detection limit of 0.1 mg/L

Chloride

Area	2.5%-ile	Mean	97.5%-ile
43	29.2	31.2	33.2
44	30.1	32.1	34.1
45	38.9	40.9	43.0
47	41.8	43.9	45.8
48	40.6	42.6	44.6

COD

Area	2.5%-ile	Mean	97.5%-ile
43	<10	<10	<10
44	<10	<10	<10
45	<10	<10	<10
47	<10	<10	12.3
48	<10	<10	12.4

Note: COD had an upper detection limit of 10 mg/L

Conductivity

Area	2.5%-ile	Mean	97.5%-ile
43	479	494	511
44	483	500	516
45	556	573	589
47	547	563	579
48	544	560	576

Dissolved Oxygen

Area	2.5%-ile	Mean	97.5%-ile
43	8.8	9.1	9.5
44	7.8	8.1	8.5
45	7.7	8.1	8.4
47	7.6	7.9	8.2
48	8.0	8.3	8.7

Nitrate

Area	2.5%-ile	Mean	97.5%-ile
43	<0.05	0.3	0.7
44	0.1	0.5	0.9
45	2.6	3.0	3.4
47	3.6	4.0	4.4
48	3.3	3.7	4.1

pH

Area	2.5%-ile	Mean	97.5%-ile
43	7.7	7.8	7.9
44	7.7	7.8	7.9
45	7.4	7.5	7.6
47	7.2	7.3	7.4
48	7.6	7.7	7.8

Sulfate

Area	2.5%-ile	Mean	97.5%-ile
43	25.2	28.4	31.7
44	25.1	28.3	31.5
45	39.0	42.3	45.7
47	40.2	43.4	46.7
48	39.1	42.3	45.6

TDS

Area	2.5%-ile	Mean	97.5%-ile
43	279	291	302
44	279	290	302
45	322	334	346
47	324	337	348
48	320	331	343

TOC

Area	2.5%-ile	Mean	97.5%-ile
43	3.7	4.1	4.6
44	3.9	4.3	4.8
45	4.3	4.7	5.2
47	4.3	4.7	5.2
48	4.5	4.9	5.3

Total Phosphorus

Area	2.5%-ile	Mean	97.5%-ile
43	<0.05	<0.05	<0.05
44	<0.05	<0.05	0.067
45	0.407	0.487	0.566
47	0.580	0.686	0.792
48	0.542	0.632	0.722

Note: Total Phosphorus had an upper detection limit of 0.05 mg/L

TSS

Area	2.5%-ile	Mean	97.5%-ile
43	<4	5.4	6.8
44	<4	5.9	8.1
45	6.6	8.8	11.0
47	9.9	19.2	28.5
48	9.2	29.2	49.2

Note: TSS had an upper detection limit of 4 mg/L

VSS

Area	2.5%-ile	Mean	97.5%-ile
43	<4	<4	<4
44	<4	<4	<4
45	<4	<4	<4
47	<4	<4	<4
48	<4	<4	6.3

Note: VSS had an upper detection limit of 4 mg/L

Appendix C

Results from the Vector AutoRegressive Model

Table C.1: Parameter Estimates from the VAR Model

Parameter	Area	θ_{21}	θ_{22}	θ_{23}	θ_{24}	θ_{25}	θ_{26}
Chloride (mg/L)	**43**	**-0.00054**	0.00033	**0.448**	**0.547**		
	44	-0.00036	0.000394	**0.482**	**0.4459**		
	45	0.0006		**0.878**			
	47	6.07E-05	2.97E-04	**0.715**	0.195		
	48	**-0.00149**	0.00076	**0.598**	**0.3137**		
Conductivity (µS/cm)	**43**	0.00276	0.0024	**0.937**	0.0308		
	44	0.00063	0.0027	**0.840**	0.123		
	45	**0.013**		**0.914**			
	47	0.0058	-0.003	**1.024**	**-0.254**	**0.16**	**0.0112**
	48	**-0.014**	**0.0108**	**0.751**	**0.226**		
Dissolved Oxygen (mg/L)	**43**	-1.70E-05	7.35E-05	**0.719**	**0.218**		
	44	-8.88E-05	9.02E-05	**0.624**	**0.3375**		
	45	4.22E-05	-2.38E-05	**0.711**	**0.240**		
	47	-1.25E-04	**1.60E-04**	**0.836**	0.0993		
	48	-5.19E-05	2.89E-05	**0.704**	**0.225**		
Nitrate (mg/L)	**43**	1.46E-05		**0.437**			
	44	3.99E-06	7.42E-06	**0.479**	**0.357**		
	45	8.26E-05		**0.637**			
	47	-4.26E-05	3.97E-05	**0.701**	-0.0389		
	48	**-2.07E-04**	6.53E-05	**0.628**	0.0549		
pH	**43**	1.73E-05	-3.98E-03	**0.496**	**0.495**		
	44	6.69E-06	-1.11E-06	**0.562**	**0.433**		
	45	-1.39E-05	9.65E-06	**0.540**	**0.455**		
	47	4.02E-05	-1.58E-05	**0.586**	**0.399**		
	48	-5.24E-05	3.59E-05	**0.336**	**0.361**	**0.302**	**-4.83E-07**
TOC	**43**	7.78E-05	1.92E-04	**0.684**	-0.120		
	44	1.01E-04	1.88E-04	**0.480**	-0.007		
	45	9.10E-05	1.64E-04	**0.439**	**0.231**		
	47	8.28E-05	1.44E-04	**0.595**	0.017		
	48	8.44E-05	9.50E-05	**0.448**	**0.255**		

Parameter	Area	θ_{21}	θ_{22}	θ_{23}	θ_{24}	θ_{25}	θ_{26}
E Coli	**43**	6.45E-05	**1.28E-04**	**0.308**	**0.389**		
	44	4.57E-05	7.46E-05	**0.48**	**0.32**		
	45	2.10E-05	8.29E-05	**0.410**	**0.400**		
	47	-2.70E-07	2.80E-05	**0.3945**	**0.4732**		
	48	-1.45E-05	7.70E-05	**0.456**	**0.325**		
TDS	**43**	0.0035	0.0034	**0.5335**	**0.3890**		
	44	0.0031	0.0036	**0.5800**	**0.3408**		
	45	**0.0036**	**-0.0106**	**0.7596**	0.1965		
	47	**0.0054**	0.0037	**0.6697**	**0.2442**		
	48	0.0034	**0.0066**	**0.6316**	**0.2751**		

Table C.2: Estimates of the Standard Error

Parameter	Area	θ_{21}	θ_{22}	θ_{23}	θ_{24}	θ_{25}	θ_{26}
Chloride (mg/L)	**43**	2.65E-04	2.40E-04	0.091	0.095		
	44	4.65E-04	4.45E-04	0.087	0.091		
	45	4.50E-04		0.046			
	47	6.44E-04	6.63E-04	0.100	0.121		
	48	5.59E-04	5.50E-04	0.078	0.073		
Conductivity (µS/cm)	**43**	2.89E-03	2.76E-03	0.100	0.101		
	44	3.30E-03	3.00E-03	0.111	0.112		
	45	4.70E-03		0.033			
	47	4.20E-03	4.30E-03	0.098	0.137	0.004	0.102
	48	4.00E-03	4.00E-03	0.085	0.086		
Dissolved Oxygen (mg/L)	**43**	1.07E-04	1.05E-04	0.094	0.095		
	44	9.03E-05	8.95E-05	0.090	0.091		
	45	9.97E-05	9.96E-05	0.098	0.098		
	47	9.14E-05	9.07E-05	0.093	0.095		
	48	1.18E-04	1.15E-04	0.094	0.096		
Nitrate (mg/L)	**43**	1.60E-05		0.084			
	44	1.71E-05	1.69E-05	0.090	0.091		
	45	9.39E-05		0.078			
	47	1.23E-04	1.23E-04	0.097	0.098		
	48	1.07E-04	1.06E-04	0.098	0.089		
pH	**43**	2.46E-05	2.43E-05	0.085	0.085		
	44	2.03E-05	2.00E-05	0.088	0.089		
	45	2.04E-05	2.03E-05	0.089	0.089		
	47	2.62E-05	2.64E-05	0.088	0.087		
	48	3.25E-05	3.34E-05	0.093	0.093	3.18E-05	9.45E-02
TOC	**43**	1.37E-04	1.36E-04	0.095	0.095		
	44	1.81E-04	1.80E-04	0.096	0.096		
	45	1.53E-04	1.53E-04	0.096	0.096		
	47	1.28E-04	1.29E-04	0.095	0.094		
	48	1.28E-04	1.28E-04	0.093	0.092		

Parameter	Area	θ_{21}	θ_{22}	θ_{23}	θ_{24}	θ_{25}	θ_{26}
E Coli	**43**	7.06E-05	7.09E-05	0.899	**0.389**		
	44	4.74E-05	4.77E-05	0.910	**0.32**		
	45	5.10E-05	5.12E-05	0.090	**0.400**		
	47	6.00E-05	5.90E-05	**0.088**	**0.4732**		
	48	6.77E-05	6.64E-05	0.094	**0.325**		
TDS	**43**	0.0028	0.0028	0.0879	0.0868		
	44	0.0029	0.0029	0.0892	0.0884		
	45	0.0037	0.0036	0.0963	0.0945		
	47	0.0030	0.0031	0.0917	0.0899		
	48	0.0031	0.0032	0.0898	0.0884		

Table C.3: Forecasts and Confidence Intervals of the Forecasts

Para- meter	Area	March 2013			April 2013			May 2013		
		Lower	Forecast	Upper	Lower	Forecast	Upper	Lower	Forecast	Upper
Chloride (mg/L)	**43**	28.04	34.50	40.96	25.91	31.99	38.06	26.69	33.02	39.34
	44	25.21	31.40	37.60	22.81	28.37	33.92	22.00	27.57	33.15
	45	45.12	47.64	50.16	39.67	41.90	44.12	34.93	37.01	39.10
	47	68.11	87.41	106.7	61.20	82.43	103.66	56.89	76.04	95.20
	48	60.88	73.28	85.68	56.83	68.46	80.08	52.42	63.41	74.41
Conductivity (µS/cm)	**43**	379	487	596	373	473	573	361	459	557
	44	380	528	676	390	507	623	374	491	608
	45	465	483	501	427	443	460	394	410	427
	47	455	694	932	395	635	875	361	595	830
	48	578	701	823	566	689	812	551	672	792
Dissolved Oxygen (mg/L)	**43**	7.41	9.48	11.55	7.07	8.89	10.71	6.67	8.46	10.25
	44	5.54	6.82	8.09	5.45	6.75	8.05	5.22	6.49	7.76
	45	4.67	5.82	6.97	4.47	5.70	6.93	4.29	5.47	6.65
	47	6.33	7.95	9.57	5.92	7.49	9.07	5.52	7.02	8.53
	48	6.18	7.95	9.72	5.85	7.39	8.93	5.46	6.98	8.49
Nitrate (mg/L)	**43**	0.11	0.14	0.17	0.05	0.06	0.08	0.02	0.03	0.05
	44	0.20	0.26	0.32	0.17	0.22	0.27	0.15	0.20	0.25
	45	3.50	4.00	4.50	2.24	2.56	2.88	1.43	1.66	1.90
	47	5.18	7.14	9.11	2.82	4.59	6.36	1.72	2.93	4.14
	48	4.49	6.39	8.30	3.03	4.50	5.98	2.04	3.10	4.17
pH	**43**	6.17	7.58	8.99	6.03	7.38	8.73	5.64	6.92	8.21
	44	6.54	7.96	9.38	6.52	7.94	9.35	6.49	7.91	9.32
	45	5.87	7.14	8.41	5.96	7.26	8.56	5.87	7.16	8.45
	47	5.98	7.30	8.62	5.82	7.08	8.33	5.81	7.08	8.35
	48	5.52	7.69	9.85	5.61	7.83	10.05	5.52	7.71	9.90
TOC	**43**	1.27	1.85	2.43	0.42	0.92	1.43	0.13	0.46	0.80
	44	0.87	1.46	2.05	0.24	0.71	1.18	0.09	0.39	0.70
	45	1.98	2.79	3.61	1.53	2.24	2.95	1.12	1.69	2.25
	47	2.41	3.40	4.40	1.27	2.15	3.02	0.79	1.38	1.98
	48	2.53	3.47	4.40	2.03	2.84	3.65	1.55	2.20	2.85

Parameter	Area	March 2013			April 2013			May 2013		
		Lower	Forecast	Upper	Lower	Forecast	Upper	Lower	Forecast	Upper
E Coli	**43**	10.64	39.36	105.3	24.83	79.34	195.02	3.86	13.97	36.94
	44	7.06	19.53	43.89	4.95	14.87	35.20	2.35	7.09	16.82
	45	3.62	10.17	23.10	3.14	8.83	20.07	1.45	4.30	10.10
	47	9.36	24.70	53.87	13.01	33.03	70.27	5.94	16.13	35.83
	48	1.41	4.46	10.88	0.92	3.13	7.98	0.37	1.37	3.66
TDS	**43**	272	386	402	256	349	377	243	337	360
	44	271	340	400	260	378	389	244	336	365
	45	339	440	509	325	446	493	313	424	475
	47	333	440	498	311	458	471	291	415	441
	48	333	482	501	310	448	465	288	417	435

Appendix D

Correlation Matrix

.

Table C.1: Correlation Matrix

	Ammonia	Chloride	COD	Conductivity	DissolvedOxy	Nitrate	pH	Sulfate	Temp	TDS	TOC	TPhos	TSS	VSS
Ammonia	1.000	0.219	0.077	0.090	-0.066	0.175	-0.191	0.181	-0.093	0.127	0.010	0.201	0.002	0.012
Chloride	0.219	1.000	0.162	0.764	0.108	0.860	-0.025	0.799	-0.256	0.683	0.125	0.834	-0.061	-0.031
COD	0.077	0.162	1.000	0.151	-0.137	0.178	-0.048	0.173	0.022	0.091	-0.020	0.207	0.075	0.059
Conductivity	0.090	**0.764**	0.151	1.000	0.061	0.708	-0.032	0.778	-0.215	0.723	0.207	0.632	-0.084	-0.035
DissolvedOxy	-0.066	0.108	-0.137	0.061	1.000	0.120	0.229	0.112	-0.632	0.197	0.128	0.122	-0.028	0.042
Nitrate	0.175	**0.860**	0.178	**0.708**	0.120	1.000	-0.171	0.829	-0.309	0.673	0.169	0.928	-0.024	-0.002
pH	-0.191	-0.025	-0.048	-0.032	0.229	-0.171	1.000	-0.068	0.030	-0.060	-0.039	-0.189	-0.110	-0.111
Sulfate	0.181	**0.799**	0.173	**0.778**	0.112	**0.829**	-0.068	1.000	-0.368	0.756	0.223	0.688	0.009	0.022
Temp	-0.093	-0.256	0.022	-0.215	**-0.632**	-0.309	0.030	-0.368	1.000	-0.424	-0.232	-0.278	-0.053	-0.113
TDS	0.127	**0.683**	0.091	**0.723**	0.197	**0.673**	-0.060	**0.756**	-0.424	1.000	0.171	0.597	-0.042	-0.011
TOC	0.010	0.125	-0.020	0.207	0.128	0.169	-0.039	0.223	-0.232	0.171	1.000	0.147	0.086	0.073
TPhos	0.201	**0.834**	0.207	**0.632**	0.122	0.928	-0.189	**0.688**	-0.278	0.597	0.147	1.000	0.006	0.025
TSS	0.002	-0.061	0.075	-0.084	-0.028	-0.024	-0.110	0.009	-0.053	-0.042	0.086	0.006	1.000	0.935
VSS	0.012	-0.031	0.059	-0.035	0.042	-0.002	-0.111	0.022	-0.113	-0.011	0.073	0.025	**0.935**	1.000