Bayesian Analysis of stream water quality data in relation to wastewater treatment plant effluent

SR-15-03, January 2015

Abel Porras, P.E.

City of Austin
Watershed Protection Department
Environmental Resource Management Division

Abstract

Environmental data taken from two central Texas streams were analyzed to determine the effects of effluent from wastewater treatment plants on the receiving streams. The two streams were chosen based on their flow regime and the nutrient concentration of the effluent. The effluent had an impact on the chemistry of the surface water for slow moving streams with high nutrient concentrations. For fast moving streams with low nutrient concentrations, the effluent mostly impacted the benthic algae cover. Changes in the ratio of carbon to nitrogen and carbon to phosphorus were detected in the stream benthic algal cover downstream of the wastewater treatment plants. This indicates active algal activity in the stream and might point to estimates of important biological parameters, such as periphyton death rates for future models. These impacts were detected using Bayesian credible intervals of the paired differences between upstream stations and downstream stations. The data was also used to construct Bayesian credible intervals for the various parameters sampled at the streams. These credible intervals can be used as default inputs into more deterministic water quality models. Finally, a linear model was developed to explore the relation between the water quality parameters sampled at the streams and the growth of stream periphyton.

Introduction

As the population of central Texas has increased over the past decades, construction of additional infrastructure has become more necessary to maintain a livable environment. The construction of wastewater treatment plants (WWTP) is just one type of facility that is needed to address the needs of a growing population. These WWTPs serve to manage solids, harmful microorganisms, oxygen demanding organic matter, and reduce or transform nutrients. The resulting treated effluent is then discharged directly to streams or sent for land application in designated areas (Metcalf and Eddy Inc, 1991). The Texas Commission on Environmental Quality (TCEQ) regulates by permit the treatment and discharge of wastewater in Texas through the Texas Pollutant Discharge Elimination System (TPDES) (TCEQ 2012). In sensitive environments like the oligotrophic streams of the Edwards Plateau region in central Texas, nutrients from treated wastewater effluent discharges may adversely alter stream ecosystems (Mabe, 2007; Herrington, 2008). While these WWTPs maintain and may comply with effluent discharge permits issued by the TCEQ, the nutrient levels allowed in these permits may still pose a threat to stream ecosystems. WWTP discharge contains elevated concentrations of nitrogen and phosphorus (Metcalf and Eddy Inc, 1991). These nutrients provide for growth of phytoplankton, periphyton and other aquatic macrophytes. The increase in instream nutrients and associated growth of photosynthetic biomass may lead to eutrophication of a water body and adversely impact the designated uses of streams.

The phenomenon of eutrophication resulting from increased nutrient addition has been known and studied since the 1960's (Ferguson, 1968). Deterministic equations were first developed to model the relations between nutrient discharge and the growth of algae theoretically; however, these equations could not reliably predict the growth of the organisms. This is especially the case when algae are in uncontrolled growth during high density blooms. Uptake of nutrients as part of the growth of photosynthetic algae and macrophytes is not a persistent nutrient sink and is dependent on the time of year. Furthermore, representation of stream nutrient assimilation by first order decay yields unreasonably high estimates of stream assimilative capacity, as nutrients will undergo continual downstream displacement by material cycling explained by the nutrient spiraling concept (Webster and Patten, 1979). Evaluation of eutrophication impacts to a receiving water from a WWTP discharge only at the plant outfall, only by instream nutrient concentrations, or only using first-order steady state decay kinetics, ignores the dynamic equilibrium between physical and biological characteristics of the stream (stream continuum concept), ignores key ecosystem health functional measures like gross primary productivity and respiration rates (Bunn et al., 1999) and ignores critical spatial and temporal scale effects (Boulton, 1999).

As an alternative to using deterministic modeling to predict potential eutrophication impacts to a stream, other more direct measurements have been suggested that do not require model creation and calibration. King et al. (2009) have documented changes in algal biomass nutrient to carbon ratios in Texas streams with wastewater addition, and have proposed nutrient to carbon thresholds as indicators of eutrophication in streams. While increases in instream phosphorus concentrations are only detectable after years of enhanced phosphorus loading, effects of phosphorus loading on the phosphorus content of periphyton is immediate, making periphyton nutrient ratio an excellent indicator of change in nutrient loading (Gaiser et al., 2004). Thus, in addition to nutrient and algal concentrations sampled in the streams, these indicator ratios can be useful water quality parameters.

A statistical approach, rather than deterministic equations, will be used in this report to examine the impacts of effluent and the growth of aquatic organisms. In particular, multiple downstream sample points from two WWTPs in central Texas were compared to upstream sites to determine the extent of influence of WWTP discharge on the growth of benthic algae. Furthermore, since a statistical approach can also provide knowledge about the potential ranges in water quality parameter values, this study will provide these ranges of values to support further use of deterministic models. The City of Austin has begun development and calibration of Water Quality Analysis and Simulation Program (WASP) models (Richter, 2010) using these data in an effort to more quantitatively describe the impact of nutrient addition from wastewater in central Texas streams.

The following steps were taken to use the statistical approach and produce appropriate models of the nutrient/algae/wastewater discharge relationship:

1. determine the difference in the water quality parameters sampled upstream of a WWTP outfall versus those water quality parameters sampled downstream of a WWTP at two different streams;
2. determine the potential range of differences at any stream;
3. quantify a range of values for those water quality parameters for possible input into the Water Quality Assessment Simulation Program (WASP) model for streams in central Texas; and
4. formulate a relation between nutrient loading from a WWTP and environmental and/or biological impact to the streams.

The goal of the study was to evaluate the impacts of WWTP effluent on streams across a range of eutrophication conditions. In this way, it is anticipated that more knowledge will be gained on the algae growth dynamics in response to wastewater addition which can then be mitigated in the future by selecting land application, beneficial reuse, or highly advanced treatment levels before discharge in sensitive watersheds.

Methods

In 2009, the City of Austin initiated a study to examine the environmental impacts of effluent from WWTPs on selected streams in central Texas. This study was comprised of three phases. The first phase was a site reconnaissance in which six streams receiving WWTP discharge were visually inspected and sampled for total phosphorus concentrations upstream, downstream at two locations, and directly at the WWTP outfall (Table 1) to determine if differences in instream phosphorus concentrations detectable by current laboratory analytical methods were present. Streams where a measureable difference in total phosphorus concentrations was found and with rock substrates suitable for periphytic algal sampling were sampled again in the second phase of the project for a full suite of physiochemical and nutrient parameters as well as periphyton cover, biomass and cell nutrient composition. The number of water quality parameters collected at each site increased from Phase I to Phase II (Table 2). This second phase provided more information in evaluating stream conditions for a more intensive data collection effort.

Table 1: Effluent Study Site List

Receiving Stream	Plant/Permit	Sites	Dates Sampled
Lake Creek	**Anderson Mill MUD (11459-001)**	**U/S = 4505: Lake Creek at Mellow Meadows** **Out = 4494: Anderson Mill MUD Outfall** **D/S1 = 4506: Lake Creek at Lake Creek Pkwy** **D/S2 = 4507: Lake Creek at Broadmeade Ave.**	**Oct 15 2009, (Phase I)** **Nov. 12 2009, (Phase II)** **Every two months from April 14, 2010 to February 25, 2011 (Phase III)**
San Gabriel South Fork	**Liberty Hill (14477-001)**	**U/S = 4511: SF San Gabriel at US 183** **Out = 4498: Liberty Hill WWTP Outfall** **D/S1 = 4512: SF San Gabriel at S. Gabriel Dr** **D/S2 = 4513: SF San Gabriel at CR268**	**Oct 15 2009, (Phase I)** **Nov. 12 2009, (Phase II)** **Every two months from April 14, 2010 to February 25, 2011 (Phase III)**
Berry Creek	Georgetown WWTP (10489-006)	U/S = 4514: Berry Creek at Airport Rd Out = 4495: Berry Creek WWTP Outfall D/S1 = 4515: Berry Creek at IH35 D/S2 = 4516: Berry Creek at CR152	Oct 16, 2009 (Phase I), Nov 12, 2009 (Phase II)
Mustang Creek	Taylor WWTP (10299-001)	U/S = 4510: Mustang Creek at 79 Out = 4499: City of Taylor WWTP Outfall D/S1 = 4509: Mustang Creek at CR619 D/S2 = 4508: Mustang Creek at CR448	Oct 16, 2009 (Phase I), Nov 12, 2009 (Phase II)
Guadalupe River	Gruene Rd (10232-002)	U/S = 4500: Guadalupe River @ Gruene Rd Out = 4497: Gruene Rd WWTP Outfall D/S1 = 4501: Guadalupe River @ Loop 337 D/S2 = 4502: Guadalupe River @ Common St	Oct 16, 2009 (Phase I), Nov 24, 2009 (Phase II)
Pedernales River	Johnson City (10198-001)	U/S = 4503: Pedernales River @ US281 Out = 4496: Johnson City WWTP Outfall D/S1 = 4504: Pedernales River nr Bradford	Oct 16, 2009 (Phase I), Nov 12, 2009 (Phase II)

Notes: U/S = upstream station; D/S1 = first station downstream of outfall ; D/S2 = second station downstream of outfall; and Out = direct sampling of WWTP outfall.

Benthic algae nutrient data was collected using the Diatom Sampling protocol (WRE, 2013) with the exception that periphyton was scraped from 25.4 cm circles on 9 to 25 rocks depending on periphyton thickness. Rock scrapings were flushed into sample containers with deionized water. The number of rock scrapings performed was recorded and used in combination with analytical results to calculate chlorophyll-a, pheophytin, periphyton biomass, periphyton carbon, phosphorus, and nitrogen in milligrams per square meter. Other calculated water quality parameters for benthic cover include periphyton biomass/chlorophyll-a ratio, carbon/nitrogen ratio, carbon/phosphorus ratio, nitrogen/phosphorus ratio, and pheophytin/chlorophyll-a ratio.

Visual algae transects were established at each site to assess the overall macroalgae percent cover and microalgae thickness at a site using the zig-zag method developed by the United States Geological Survey (Mabe, 2007). Transects were run in a zig-zag pattern over the length of the reach, and divided into 50 equally spaced points. At each point a 1 ft^2 area was established and the percent cover of macroalgae was categorized as less than 5 percent, 5-25 percent, 50-75 percent or more than 75 percent within the quadrat. The thickness of microalgae at each point was categorized as rough, slimy, visible, 0.5 to 1 mm thick, or greater than 1 mm thick.

Table 2: Water Quality Parameters collected in Phase II.

Description	Water Quality Parameters
Water quality	Ammonia, Nitrate/Nitrite, Total Kjeldahl Nitrogen (TKN), Orthophosphorus, Total Phosphorus, Phytoplankton Chl-a\pheophytin, Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD)
ERM in-house	In-vivo chl-a, optical brighteners, turbidity
Benthic Algae Nutrients	Ammonia, Nitrate/Nitrite, Total Kjeldahl Nitrogen (TKN), Orthophosphorus, Total Phosphorus, Total Suspended Solids, Volatile Suspended Solids, Organic Carbon, Chl-a/Pheophytin
Field Parameters	Dissolved Oxygen, pH, Conductivity, Water Temperature, Flow, and Light Extinction Coefficient
Visual Habitat	EPA HQI and canopy cover
Algae Transects	Macroalgae percent cover and microalgae thickness

Phase III consisted of bi-monthly monitoring (beginning on April 2010) of the Water Quality, Benthic Algae Nutrients, Field Parameters, and Visual Algae parameter suites listed in Table 2 on a select number of creeks. This selection was based on two factors: flow regime and efficiency of the discharging WWTP. Each creek was assigned to one of two flow regimes (fast flowing creeks or slow flowing creeks) and one of two efficiency characteristics (inefficient WWTP or efficient WWTP). This broad generalization generated pairs of flow regime/WWTP characteristics for each stream. The combination of efficient WWTPs discharging onto fast flowing creeks and inefficient WWTPs discharging onto slow flowing creeks were preferred. The reason for this preference is that it allows for a more focused sampling routine on a minimal number (in this case, two) of distinct streams.

Based on these criteria, two creeks, the South Fork of the San Gabriel River and Lake Creek, respectively, were selected for continued bi-monthly monitoring for one year. That is, South Fork of the San Gabriel River had the lowest nutrient concentrations in the released effluent with the highest stream flow rate, while Lake Creek had the highest nutrient concentration in the released effluent with the lowest stream flow rate. The basis for these criteria is the supposition that these specific combinations of factors can, in principal, characterize two distinct responses of the creek to the effluent. And, if the combinations are at the limits of dissimilarity, then the responses would, in essence, provide upper and lower limits to any stream's response to WWTP discharge in Central Texas.

As a consequence of the distinctness of Lake Creek and San Gabriel-South Fork, data obtained from each stream could not be combined or grouped together. Thus, each water quality parameter at each station at each stream had from 6 to 8 data points. This is typically not a large enough sample size to make statistical determinations or inferences based on traditional (or frequentist) statistics. So, to accomplish the objectives of this report, Bayesian statistics were utilized with frequentist statistics used as a validation tool.

This report will first look at the paired differences in upstream versus downstream water quality parameters sampled at each stream (as listed in Table 2) using Bayesian credible intervals. Then, the actual upstream and downstream water quality parameter values will be assessed separately with Bayesian credible intervals used as a possible default range to be input into WASP. Finally, the data will be examined using linear regression techniques in an attempt to predict the amount of organism growth based on the nutrient loading and/or the physical/chemical properties of the stream. A brief discussion on Bayesian and frequentist statistics will be included to assist the uninitiated reader.

Statistical Analysis

Bayesian statistics stems from Bayes Theorem which states that:

$$p(\theta|y) = p(y|\theta) \cdot p(\theta)/p(y) \qquad (1)$$

In its most general form, θ and y can be referred to as *events*, or a set of outcomes from an experiment. Thus, the theorem evaluates the probability of an event happening given the occurrence of the other event. When one considers θ to be a set of unknown parameters[1] and y to be the data set, then Bayes Theorem can evaluate the probability of the set of unknown parameters, $p(\theta|y)$, based on a subjective assessment of the unknown parameters, $p(\theta)$, which is modified to account for the evidence from the data set, $p(y|\theta)$.

Specifically, the theorem asserts that the probability of the unknown parameters given the data, $p(\theta|y)$, is equal to the likelihood of the data given the parameters, $p(y|\theta)$, multiplied by the probability of the parameters, $p(\theta)$, divided by the normalizing constant $p(y)$. Each of these terms are probability densities with $p(\theta|y)$ and $p(\theta)$ typically referred to as the posterior density and the prior density, respectively. The posterior density of the parameters is the unknown, and the prior density is an educated guess about the distribution of the parameters. If an educated guess is unavailable, then uninformative, or large, distributions are used. Once the posterior density is calculated, it can be used as a prior density for future studies.

The term $p(y|\theta)$ denotes the likelihood of the data given some hypothesis of the parameters. That is, if one postulates that the mean of some parameter, θ, is μ and is normally distributed, then the likelihood that the data, y, comes from that distribution with mean of μ can be calculated by finding the inverse to the normal distribution function with a mean of μ at y. Each data point has some likelihood (i.e. a point on the inverse normal distribution curve), and the cumulative probability of all the data points can be calculated by multiplying each likelihood together. If the mean is unknown (which it typically is), then a range of means is utilized in the calculation using Monte Carlo methods. The result is the probability distribution, $p(y|\theta)$. The product of $p(y|\theta)$ with the prior distribution produces the posterior distribution, $p(\theta|y)$. Obtaining the 2.5 and 97.5 percentiles from the posterior distribution will provide the Bayesian credible intervals used in this report.

The product of the likelihood function and the prior distribution produces the posterior distribution. A feature of Bayesian statistics is in the use of the prior distribution. If a large enough data sample is used, then the likelihood function would “dominate” and the prior distribution would become less relevant. However, if the data set is small, then the prior distribution might “dominate”. If this prior distribution is informative, then the prior distribution tends to have a greater influence on the posterior distribution. To mitigate the influence of the prior, one aspires to update the priors as one continues gathering enough data to make a conclusive case on the values of the parameters.

---

[1] For this report we’ll distinguish between the terms “parameters” and the more specific “water quality parameters”. When used without the adjective, “parameters” will refer to statistical parameters, such as mean, standard deviation, slope, intercept, etc. In the more specific case, “water quality parameters” will refer to dissolved oxygen, temperature, ph, the nutrient concentrations, the ratios, etc.

Frequentist statistics works in the opposite fashion. That is, frequentists look solely to find the probability of the data given the parameters, $p(y|\theta)$. However, this approach doesn't use Bayes' Theorem. Instead, the data are treated as one set of realizations out of many realizations from a set of random variables given the non-random (or fixed) parameters[2]. As a result, the outputs are interpreted not as probabilities, but as long run frequencies. To compute these frequencies, one must assume that the Central Limit Theorem operates on the data. However, the Central Limit Theorem is accurate for data sets regardless of distributional assumptions, so long as the data sets approach large sample sizes. Thus, for small data sets, the assumptions either will not apply or provide large uncertainty in their estimates. The calculation of the parameters in question using frequentist statistics comes from the following:

$$[\text{LCI},\text{UCI}]=\bar{x} \pm t_{1-\frac{\alpha}{2};n-1} \cdot s/\sqrt{n} \tag{2}$$

For this equation, LCI and UCI refer to the lower and upper confidence intervals, respectively. The term $\bar{x}$ denotes the average of the measurements; $t_{1-\alpha/2;n-1}$ signifies the value of the Student's t-distribution with probability 1-α/2 and n-1 degrees of freedom; α is the Type I error rate; n is the number of samples; and s is the standard deviation of the measurements.

Another drawback of frequentist statistics comes from the rigidity of the hypotheses of the parameters. Frequentists explicitly assume that the null hypothesis is true for each of its parameters. That is, frequentists start with the assumption that one cannot statistically distinguish any of its parameters (i.e. mean, slope, etc) from zero, and the burden of proof lies with the analyst to show that the data indicates otherwise. This is in contrast to Bayesian statistics, where the hypotheses of the parameters are more flexible and are explicitly stipulated in the prior distributions. This explicit hypothesis in the prior distribution is then either confirmed or rendered irrelevant by the data.

Statistical Models

Regardless of the approach used, inference on the data comes from the models developed. Two different statistical models will be used in this report. The first will be the constant mean model. In this model, a constant mean will be assumed for each station at each stream. Within this model, two different means will be computed. The first mean is the mean paired difference. This mean will examine the difference between the upstream stations with the two downstream stations. The concentration of an upstream water quality parameter will be paired with the concentration of a downstream water quality parameter at each date. Thus, this comparison will focus on whether an impact has occurred. The second mean estimated is the actual mean of all the data for each water quality parameter. This mean will include the year round data and, as a consequence, will have the additional variability from seasonal measurements. By estimating both of these means at every station, the estimated means can be compared to other means between and within streams.

---

[2] Contrast this with the Bayesian framework where the data are considered fixed and the parameters are considered as random variables.

The second model to be used is a linear regression model. This model will assert that a certain water quality parameter is linearly dependent on other water quality parameter(s). Thus, in this second statistical model, the statistical parameters of interest are the slope and intercept. The equation used in this model is:

$$y = \alpha + \beta \cdot x \qquad (3)$$

This model can be extended to multivariate cases by incorporating linear algebra.

The statistical analyses described above should provide a supportable conclusion about whether the discharge of the wastewater treatment plant is having a deleterious impact on the water quality downstream. If so, then improvements to effluent quality may result in long term improvement in downstream water quality and provide guidance on appropriate effluent limits in future permits planning on discharge to similar streams. In this way, impairments to the ecology of these receiving streams can be avoided.

Results

Constant Mean Models

The results from the statistical analysis can be investigated by first partitioning the data into four categories. These categories include:

1. Physico-chemical parameters in the surface water
2. Nutrients and algal matter in the surface water
3. Nutrients and algal matter in the benthic cover
4. Nutrient and algal matter ratios in the benthic cover

Within each of these categories, paired differences between upstream and downstream locations at each stream will be discussed first. That is, an upstream data point was paired with its downstream data point for every site visit. For each pair, the upstream data point was subtracted from the downstream data point. Thus, positive values signify an increase in downstream water quality parameter values, and negative values indicate a decrease in the downstream water quality parameter values.

This will be followed by a general characterization of upstream and downstream locations at each stream for each water quality parameter without looking at paired differences. This provides a general sense of the magnitude of expected water quality parameter values throughout the year at each site and at each stream.

For each of the constant mean models, a 95% Bayesian Credible Interval will be presented and denoted in the Tables by a lower credible interval (LCI) at the 2.5 percentile of the mean and an upper credible interval (UCI) at the 97.5 percentile of the mean. And, as stated above, the streams were evaluated separately due to their distinct characteristics. This distinctness is often present in the different responses of the creek to the effluent, as will be shown.

Physico-chemical parameters in the surface water

Dissolved oxygen, temperature, pH, and specific conductivity make up the water quality parameters in the physico-chemical category of the surface water. These are instantaneous measurements, and represent general habitat conditions of the stream.

Results from the Bayesian analysis of paired differences showed that effluent increased the amount of dissolved oxygen, temperature, and pH in downstream sections of Lake Creek (see Table 3). In some cases, notably the summer months, dissolved oxygen was greatly increased at downstream sections leading to over a 10 mg/L increase in dissolved oxygen. This might be attributed to the oxygenated levels in the effluent. The downstream differences in South Fork - San Gabriel were not as pronounced with roughly 2 mg/L or degrees Celsius increases in dissolved oxygen and temperature, respectively, at downstream sections as shown in Table 4.

Table 3: Mean Concentration in Lake Creek Paired Differences

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Dissolved Oxygen (mg/L)	1.58	8.24	5.24	12.01	Yes	Yes
Temperature (^{o}C)	-0.12	3.55	1.72	5.33	No	Yes
pH (std units)	-0.12	0.35	1.15	1.63	No	Yes
Conductivity (µS/cm)	-118	12.6	-166	-31.3	No	Yes

Table 4: Mean Concentration in South Fork – San Gabriel Paired Differences

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Dissolved Oxygen (mg/L)	0.758	2.35	0.314	1.88	Yes	Yes
Temperature (^{o}C)	1.28	3.76	0.11	2.58	Yes	Yes
pH (std units)	-0.53	1.09	-1.14	1.07	No	No
Conductivity (µS/cm)	-125	36.5	-124	-30.3	No	No

The mean concentrations in each of the physio-chemical water quality parameters are depicted in Tables 5 and 6 below. The high dissolved oxygen concentrations and pH at downstream sections relative to the upstream sections are readily apparent in Lake Creek as are the low specific conductivity levels.

Table 5: Mean Concentration in Lake Creek Water Quality Parameters

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Dissolved Oxygen (mg/L)	2.9	6.9	7.4	11.3	11.2	15.2
Temperature (^oC)	16.8	24.4	18.1	25.2	19.5	26.6
pH (std units)	7.2	7.7	7.3	7.8	8.6	9.0
Conductivity (µS/cm)	747	767	702	722	650	670

Table 6: Mean Concentration in San Gabriel-South Fork Water Quality Parameters

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Dissolved Oxygen (mg/L)	7.2	10.5	7.6	10.8	8.5	12.1
Temperature (^oC)	19.3	26.5	20.7	27.8	20.1	27.1
pH (std units)	7.96	8.29	8.11	8.47	8.02	8.34
Conductivity (µS/cm)	458	585	414	541	407	534

For San Gabriel-South Fork, the mean concentrations appear similar at each station. This is due to grouping all year round data together at each station without examining the paired differences between them. The results in Tables 5 and 6 provide an overall, year-round assessment of the mean of the water quality parameters.

Nutrients and algal matter in the surface water

The remaining water quality parameters sampled in the surface water consisted of nutrients, total suspended solids, chlorophyll-a, and pheophytin. The suite of nutrients analyzed further separated nitrogen and phosphorus into their organic and inorganic forms. The nutrient measurements quantified the available food source for algal matter.

Table 7: Mean Concentration in Lake Creek Paired Differences

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Ammonia (mg/L)	-0.013	0.13	-0.045	0.095	No	No
Nitrate (mg/L)	3.15	11.7	1.70	10.1	Yes	Yes
TKN (mg/L)	-0.20	0.900	-0.072	1.02	No	No
Orthophosphorus (mg/L)	1.02	2.085	0.5756	1.64	Yes	Yes
Phosphorus (mg/L)	1.04	2.126	0.651	1.73	Yes	Yes
TSS (mg/L)	-3.78	0.632	-2.83	1.57	No	No
Chlorophyll-a (µg/L)	-10.3	7.96	-4.71	13.55	No	No
Pheophytin (µg/L)	-2.89	4.95	0.136	8.011	No	Yes

Table 8: Mean Concentration in South Fork – San Gabriel Paired Differences

Parameter	Downstream 1		Downstream 2		Downstream 1	Downstream 2
	LCI	UCI	LCI	UCI	Significant Diff	Significant Diff
Ammonia (mg/L)	-0.011	0.043	-0.030	0.034	No	No
Nitrate (mg/L)	.038	0.139	-0.067	0.049	Yes	No
TKN (mg/L)	-0.082	0.142	-0.183	0.079	No	No
Orthophosphorus (mg/L)	-0.005	0.017	-0.012	0.013	No	No
Phosphorus (mg/L)	-0.004	0.017	-0.009	0.012	No	No
TSS (mg/L)	0.164	2.074	-1.182	1.01	Yes	No
Chlorophyll-a (µg/L)	-5.79	9.322	-2.922	14.02	No	No
Pheophytin (µg/L)	-1.865	3.073	-0.8107	4.812	No	No

For nutrients and algal matter in surface water, Lake Creek showed statistically significant increases downstream of the WWTP discharge for nitrate, orthophosphorus, phosphorus, and pheophytin as opposed to South Fork- San Gabriel which showed only significant increases in Nitrate and TSS and only at the closest downstream segment (Downstream 1). The mean nutrient concentrations in the surface water for each of the water quality parameters throughout the year are given in Tables 7 and 8 below.

Table 9: Mean Concentration in Lake Creek Water Quality Parameters

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Ammonia (mg/L)	<DL	0.2	0.1	0.2	0.1	0.2
Nitrate (mg/L)	<DL	6.4	6.4	12.8	3.2	12.8
TKN (mg/L)	0.7	1.4	0.7	1.4	0.7	1.75
Orthophosphorus (mg/L)	<DL	0.42	1.26	2.1	0.84	1.68
Phosphorus (mg/L)	<DL	0.43	1.29	1.72	0.86	1.72
TSS (mg/L)	3.3	6.6	0.50	1.65	3.3	6.6
Chlorophyll-a (µg/L)	3.7	14.8	3.7	14.8	7.4	14.8
Pheophytin (µg/L)	<DL	5.8	0.8	6.3	3.1	9.1

Table 10: Mean Concentration in San Gabriel-South Fork Water Quality Parameters

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Ammonia (mg/L)	<DL	0.025	<DL	0.027	<DL	0.03
Nitrate (mg/L)	1.19	4.42	1.19	4.42	1.19	4.42
TKN (mg/L)	0.43	1.49	0.46	1.5	0.4	1.45
Orthophosphorus (mg/L)	0.033	0.16	0.038	0.17	0.032	0.16
Phosphorus (mg/L)	0.055	0.21	0.058	0.22	0.115	0.21
TSS (mg/L)	0.66	2.36	1.5	3.4	0.57	2.28

Note that nitrate at Lake Creek tends to be about 3 times higher in concentration than in San Gabriel-South Fork. Another consideration in this analysis is that many of the measurements (especially for ammonia) were below the detection limits. However, this was mitigated by imputing the non-detect measurements assuming a log-normal distribution. Using these imputed values, calculations on the paired differences and mean concentrations were performed. But, if the mean concentration was below the detection limit, then “<DL” was used to denote the value.

Nutrients and algal matter in the benthic cover

Nutrients and algal matter were also sampled in the benthic cover of each stream. These samples consisted of total phosphorus and nitrogen taken from rock scrapings. These measurements quantified the amount of nutrients taken up by the algae, which manifested in the benthic cover.

Table 11: Mean Concentration in Lake Creek Paired Differences in the Benthic Cover

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Phosphorus (mg/m^2)	-353	481	-97.0	806	No	No
Nitrogen (mg/m^2)	-333	179	-324	181	No	No
Periphyton Dry Weight (mg/m^2)	-21600	3090	-16800	6340	No	No
Pheophytin (mg/m^2)	-218	681	-481	352	No	No
Periphyton Carbon (mg/m^2)	-926	1130	-722	1360	No	No

Table 12: Mean Concentration in South Fork – San Gabriel Paired Differences in the Benthic Cover

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Phosphorus (mg/m^2)	46.4	138	-30.2	60.3	Yes	No
Nitrogen (mg/m^2)	244	905	-29.1	553	Yes	No
Periphyton Dry Weight (mg/m^2)	-286.6	10980	369.8	12100	No	Yes
Pheophytin (mg/m^2)	18.03	575.5	-154.8	347.3	Yes	No
Periphyton Carbon (mg/m^2)	97.18	1724	-233.8	1124	Yes	No

The results from the analysis show that while effluent on Lake Creek had minimal impact on benthic cover in downstream sections, San Gabriel-South Fork had a more pronounced impact on downstream section of benthic cover compared to its lack of impact on downstream sections of surface water. Nitrogen, Phosphorus, Pheophytin, and Periphyton Carbon all had significantly higher concentrations in the benthic cover downstream of the discharge than upstream.

The mean nutrient concentrations throughout the year are provided in Tables 13 and 14 below. Note that even though San Gabriel had significant differences in benthic cover, Lake Creek had consistently higher nutrient concentrations in the benthic cover across all cross sections.

Table 13: Mean Concentration in Lake Creek Water Quality Parameters in the Benthic Cover

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Phosphorus (mg/m^2)	232	678	250	710	330	815
Nitrogen (mg/m^2)	721	2176	630	2077	634	2083
Periphyton Dry Weight (mg/m^2)	14910	31227	12180	28672	13510	29855
Pheophytin (mg/m^2)	14.3	37.5	16.4	40.1	11.1	34.6
Periphyton Carbon (mg/m^2)	297	2865	397	2973	663	3264

Table 14: Mean Concentration in San Gabriel-South Fork Water Quality Parameters in the Benthic Cover

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Phosphorus (mg/m^2)	18	72	48	119	24	77
Nitrogen (mg/m^2)	386.6	896	568	1079.4	468	959.2
Periphyton Dry Weight (mg/m^2)	7220	16700	8610	17800	9250	18500
Pheophytin (mg/m^2)	2.80	8.68	4.9	11.4	3.46	9.37
Periphyton Carbon (mg/m^2)	10	1385	796	2495	262	1875

Nutrient and algal matter ratios in the benthic cover

Finally, in many cases, knowing the nutrient ratios or algal matter to nutrient ratios in a stream can provide information on the extent to which nutrients get converted to algal matter.

Table 15: Mean Concentration in Lake Creek Paired Differences

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Periphyton:Chlorophyll-a	-232	34.5	-152	93.7	No	No
Carbon:Nitrogen	-0.652	0.724	-0.332	1.05	No	No
Carbon:Phosphorus	-18.7	-1.58	-23.2	-6.44	Yes	Yes
Nitrogen:Phosphorus	-16.4	-0.788	-19.8	-9.27	Yes	Yes
Pheophytin:Chlorophyll-a	-1.77	1.78	-1.09	1.32	No	No
Mass:Carbon	-11.5	-1.50	-9.71	0.738	Yes	Yes
Chlorophyll-a:Carbon	-4.25	3.72	-3.52	2.90	No	No

Table 16: Mean Concentration in South Fork – San Gabriel Paired Differences

Parameter	Downstream 1		Downstream 2		Downstream 1 Significant Diff	Downstream 2 Significant Diff
	LCI	UCI	LCI	UCI		
Periphyton:Chlorophyll-a	-641.2	726.6	-323.8	1129	No	No
Carbon:Nitrogen	-1.078	0.088	-0.897	0.286	No	No
Carbon:Phosphorus	-213.3	-60.89	-102.9	47.67	Yes	No
Nitrogen:Phosphorus	-70.46	-23.82	-21.22	25.37	Yes	No
Pheophytin:Chlorophyll-a	-0.995	1.117	-0.8181	1.224	No	No
Mass:Carbon	-4.354	3.908	-1.062	7.025	No	No
Chlorophyll-a:Carbon	-0.03445	0.05849	-0.05826	0.03428	No	No

For benthic cover nutrient ratios, downstream sections in both streams showed significantly lower carbon:phosphorus and nitrogen:phosphorus ratios than upstream sections with South Fork – San Gabriel showing bigger differences in the ratios than Lake Creek. This would indicate that phosphorus is the limiting nutrient in both creeks with perhaps faster consumption of phosphorus by algae in South Fork – San Gabriel. Furthermore, downstream sections of South Fork – San Gabriel had a significantly higher periphyton:carbon ratio than upstream sections suggesting a lower death rate of periphyton in South Fork compared to Lake Creek. Downstream sections of Lake Creek had lower mass to carbon ratios than upstream sections.

The range of the mean values of the ratios is given in Tables 17 and 18 below.

Table 17: Mean Concentration in Lake Creek Water Quality Ratios

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Periphyton:Chlorophyll-a	99	350	3	231	76	315
Carbon:Nitrogen	0.94	1.9	0.95	1.94	1.18	2.2
Carbon:Phosphorus	19.3	34.9	11.5	25.7	6.7	21.9
Nitrogen:Phosphorus	17.6	23.9	10.7	16.9	4.6	11
Pheophytin:Chlorophyll-a	0.165	0.36	0.215	0.42	0.176	0.37
Mass:Carbon	7.6	16.8	3	11.7	4.8	13
Chlorophyll-a:Carbon	0.035	0.086	0.038	0.088	0.019	0.072

Table 18: Mean Concentration in San Gabriel-South Fork Water Quality Ratios

Parameter	Upstream		Downstream 1		Downstream 2	
	LCI	UCI	LCI	UCI	LCI	UCI
Periphyton:Chlorophyll-a	379	1087	370	1071	483	1231
Carbon:Nitrogen	2.18	3.23	1.82	2.85	1.99	3.00
Carbon:Phosphorus	110	272	-25	116	90	237
Nitrogen:Phosphorus	42	87	1	43	49	92
Pheophytin:Chlorophyll-a	0.01	0.22	0.09	0.33	0.07	0.3
Mass:Carbon	4.36	10.9	3.84	10.71	6.36	13.4
Chlorophyll-a:Carbon	0.011	0.06	0.012	0.07	0.012	0.052

Tables 3 through 18 above depict the Bayesian credible intervals of the mean paired difference in upstream versus downstream concentrations and the mean concentrations for several parameters at each stream and at each station within a stream. A set of tables for the mean concentrations can be found in Appendix A using frequentist's confidence intervals for comparison.

Linear Regression Models

A linear regression model was applied to determine whether nutrient concentrations in either the surface water or benthic cover were related to concentrations of algal matter in the surface water or benthic cover. However, in constructing a linear regression model, several assumptions had to be made. First, only data gathered in the summer months (i.e. June and August of 2010) were used. This allowed the growth of algal matter to reach its maximum potential. Since algal growth is mitigated during the winter months with temperature limitations on growth rates, including low concentrations of algal with high nutrient concentration effluent might lead to some confounding by temperature and light conditions. Accounting for this low amount of algae would require an additional model, which will be considered in a future study that seeks to unify the data collected here with a more complex non-linear model. Another assumption made was that parsimony was favored over complexity. Thus, linear models with a limited number of factors were preferred over non-linear models or those with extensive factors. This inclination for parsimony is due to the fact that this study of WWTP effluent on creeks in central Texas is currently in the exploratory stages. More data would provide a more focused analysis on potential effects of WWTP effluent. The final assumption was that data on the ratios were ignored. This was due to the fact that most of the information in the ratios was already in the nutrient and algal matter concentration data used.

Based on these assumptions, two linear models were surmised from the data. The first model found that the concentration of Pheophytin in the benthic cover increased as the concentration of Total Kjeldahl Nitrogen in the benthic cover increased. The second model found that the concentration of Chlorophyll-a in the benthic cover also increased as the concentration of phosphorus in the benthic cover increased. The table below shows the estimates of the intercept, α, and the slope, β, along with their 95% credible intervals.

Table 19: Bayesian Credible Intervals for the Parameters in the Linear Regression Model

		2.5%-ile	**Median**	**97.5%-ile**
Model 1:	α (intercept)	-321	-221	-124
TKN-Pheophytin	β (slope)	13.7	14.8	16
Model 2:	α (intercept)	2318	2392	2468
Phosphorus-Chl-a	β (slope)	171	176	181

The first model shows that for every mg/L increase in TKN, the concentration in pheophytin increases by between 13.7 and 16 µg/L. Similarly, the second model shows that for every mg/L increase in phosphorus, the concentration in chlorophyll-a increases by between 171 and 181 µg/L. The intercepts are of lesser interest and show the theoretical concentration of the algal matter when there is no nutrient concentration. Of course, negative concentrations (as seen in Model 1) do not make sense and are artifacts of the linear model used. It is anticipated that more data would provide opportunities for more rigorous and complex analyses.

Discussion

Suppose one had the assignment of choosing where to locate a WWTP and the level of efficiency (or treatment) of the WWTP. That is, one could choose from a wide selection of locations ranging from slow flowing streams to fast flowing streams and between inefficient WWTPs to efficient WWTPs. Which of these choices would lead to a minimal impact to the receiving stream? Is there a certain combination of choices that would be ideal? What selection could be considered non-degradation in an ecological or regulatory sense?

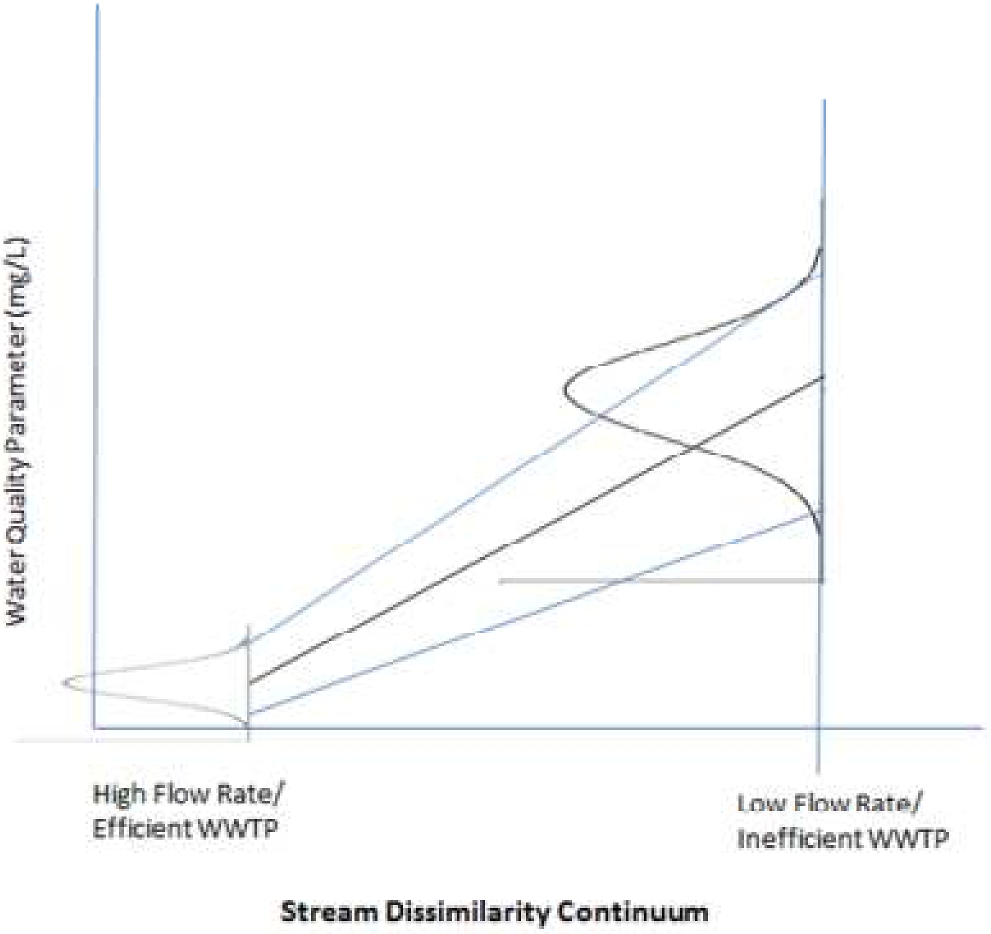
Data collection and analysis conducted by the Watershed Protection Department (WPD) sought to answer these questions by collapsing these two receiving water and effluent limit decisions into one by evaluating two distinct stream-WWTP pairs and placing it in a stream dissimilarity continuum. WPD obtained data from a slowing flowing stream with an inefficient WWTP (Lake Creek) and a fast flowing stream with an efficient WWTP (San Gabriel-South Fork). Thus, by evaluating the impacts on the two streams with these distinct combinations, the results would encompass two ends of a response continuum from any stream in central Texas.

Results from this analysis show that in either case, the impacts can still be detected on the receiving stream. However, the impacts differ in their characterization. Effluent from an ineffective WWTP on a slow flowing stream would increase the concentration of nutrients and algal matter in the surface water body. Effluent from an effective WWTP on a high flowing stream would more likely increase the downstream concentrations of nutrients and algal matter in the benthic cover of the receiving stream. In both cases, water temperature would increase potentially providing favorable conditions for the growth of algae, and nutrient ratios would increase potentially indicating changing trophic status of the receiving stream.

The implications from this study are that any WWTP-stream pairing would generate impacts on the receiving water body. However, this conclusion at this point in data collection is not definitive. This report recommends the following actions be taken to expand the study.

1. More data is needed at each of the two streams. Data was only collected for one year. This allowed only one cycle of seasonal variations. Data from the winter months (when algal growth is minimal) was grouped with data from the summer months (when algal growth is favorable) in the constant mean models and was not utilized for the linear regression models. For a more accurate assessment of the impacts (especially during the summer months when conditions are more conducive to algal growth), several data points need to be collected for each season, possibly entailing at least four or five more years.

2. More streams should be sampled. This study is based on the premise that studying two dissimilar streams will contain the range of responses for streams in central Texas. If this premise is correct, then one should see continuity in responses for streams in the middle of this stream dissimilarity continuum. In fact, there is already evidence of this in the data analyzed. Some water quality parameters, such as phosphorus in the surface water, show small mean concentrations with small variances in the concentration for South Fork – San Gabriel. The same water quality parameter will show larger mean concentrations with larger variances in the concentration for Lake Creek. This might indicate that one can interpolate between these responses for streams in the middle. Conceptually, such a response would look like the figure below.



If this premise is incorrect, then the two factors can be treated as independent (as two independent axes), and a 3-dimensional response surface can be developed instead of the current 2-dimensional response surface.

3. The model predicting conditions for algal growth was based on a generalized linear model. Such natural phenomena will not necessarily follow this linear pattern. In fact, as discussed in the introduction, coupled differential equations have been used to model this growth. One of the benefits of Bayesian statistics is that it allows one to test the likelihood of one model (say a linear model) versus a non-linear model (the coupled differential equation). More time and data is needed for the analyst to conduct such a test.

References

Boulton, A.J. 1999. An overview of river health assessment: philosophies, practice, problems and prognosis. Freshwater Biology 41: 469-471.

Bunn, S.E., and P.M. Davis, T.D. Mosisch. 1999. Ecosystem measures of river health and their response to riparian and catchment degradation. Freshwater Biology 41:333-345.

Ferguson, F. A. 1968. A Nonmyopic Approach to the Problem of Excess Algal Growths. Environmental Science and Technology 2:188-193.

Gaiser, E.E., Scinto, L.J., Richards, J.H., Jayachandran, K., Childers, D.L., Trexler, J.C., Jones, R.D. 2004. Phosphorus in periphyton mats provides the best metric for detecting low level P enrichment in an oligotrophic wetland. Water Resources 38: 507–516.

Helsel, D. R. 2005. Nondetects and Data Analysis: Statistics for Censored Environmental Data. John Wiley & Sons, Inc. Hoboken, New Jersey.

Herrington, C. 2008. Impacts of the proposed HCWCID 1 wastewater discharge to Bear Creek on nutrient and DO concentrations at Barton Springs. City of Austin Watershed Protection and Development Review Department, SR-08-05.

King, R.S., K.O. Winemiller, J.M. Taylor, J.A. Back, and A. Pease. 2009. Development of Biological Indicators of Nutrient Enrichment for Applications in Texas Streams. Texas Commission on Environmental Quality: Water Quality Assessment Program.

Mabe, J.A. 2007. Nutrient and Biological Conditions of Selected Small Streams in the Edwards Plateau, Central Texas, 2005–06, and Implications for Development of Nutrient Criteria. United States Geological Survey Scientific Investigations Report 2007–5195.

McCormick, P. V. and R. J. Stevenson. 1998. Periphyton as a Tool for Ecological Assessment and Management in the Florida Everglades. J. Phycol. 34: 726-733.

Metcalf and Eddy, Inc. 1991. Wastewater Engineering: Treatment/Disposal/Reuse. Third Edition. McGraw-Hill Book Company, New York.

Montgomery, D., E. Peck, and G. Vining. 2006. Introduction to Linear Regression Analysis. Fourth Edition. John Wiley & Sons, Inc. Publication, Hoboken, New Jersey.

Richter, A. 2010. Comparison of Intermittent and Continuous Discharges on Bear Creek in WASP7.3 for Phytoplankton and Benthic Algae. City of Austin Watershed Protection and Development Review Department SR-10-01.

Richter, A. 2012. Modeling Benthic Algae Growth in Lake Creek, a High Nutrient Stream in Austin, TX. City of Austin Watershed Protection Department SR-12-07.

Texas Commission on Environmental Quality (TCEQ) 2012. Draft. Procedures to Implement the Texas Surface Water Quality Standards. Water Quality Division. RG-194. January 2012.

Water Resource Evaluation (WRE) Section, City of Austin. 2010. Standard Operating Procedures Manual. City of Austin Watershed Protection Department.

Webster, J.R., and B.C. Patten. 1979. Effects of watershed perturbation on stream potassium and calcium dynamics. Ecological Monographs 49: 51-72.

Appendix A

Table A.1: Confidence Intervals of the Mean for Lake Creek Sites

Upstream Station/ above Outfall

Parameter[1]	Media[2]	Average	StDev	Count	LCI	UCI	Units
DO	SW	4.68	2.22	8	2.82	6.53	mg/L
Temp	SW	19.69	6.35	8	14.4	25.0	°C
pH	SW	7.43	0.19	8	7.27	7.59	Std units
Ammonia	SW	0.01	0.01	7	0.00	0.02	mg/L
Nitrate	SW	0.03	0.07	7	<DL	0.10	mg/L
TKN	SW	0.49	0.32	7	0.19	0.79	mg/L
OrthoP	SW	0.01	0.01	7	0.00	0.01	mg/L
Phosphorus	SW	0.02	0.02	8	0.01	0.03	mg/L
TSS	SW	3.30	2.92	7	0.60	6.00	mg/L
Chlorophyll-a	SW	4.70	6.14	7	<DL	10.38	µg/L
Pheophytin	SW	2.51	1.78	7	0.87	4.16	µg/L
Conductivity	SW	770.38	115.82	8	673.6	867.2	uS/cm
Phosphorus	BC	165.94	76.92	7	94.8	237.1	mg/ m^2
Nitrogen	BC	1538.71	722.57	7	870	2207	mg/m^2
Peri:Chloro	BC	247.00	88.74	7	165	329	Ratio
Periphyton	BC	23446	8977	7	15,100	31,700	mg/m^2
Pheophytin	BC	26.68	15.89	7	12	41	mg/m^2
C:N Ratio	BC	1.39	0.63	6	0.73	2.05	Ratio
C:P Ratio	BC	28.77	10.70	6	17.5	40.0	Ratio
N:P Ratio	BC	21.02	5.20	7	16.2	25.8	Ratio
Pheo: Chloro	BC	0.25	0.10	7	0.16	0.35	Ratio
Mass:C	BC	13.26	2.11	6	11.0	15.5	Ratio
Chloro: Carbon	BC	0.06	0.02	6	0.04	0.08	Ratio
Periphyton Carbon	BC	1798	921	6	831	2765	mg/m^2

1. The key to the abbreviated parameters is as follows: DO=dissolved oxygen, Temp = temperature, TKN = Total Kjeldahl Nitrogen, OrthoP = Orthophosphorus, TSS = Total Suspended Solids, Peri:Chloro = Periphyton to Chlorophyll-a Ratio, C:N Ratio = Carbon to Nitrogen Ratio, C:P Ratio = Carbon to Phosphorus Ratio, N:P Ratio = Nitrogen to Phosphorus Ratio, Pheo:Chloro=Pheophyton to Chlorophyll-a Ratio, Chloro:Carbon=Chlorophyll-a to Carbon Ratio.
2. The key to the abbreviated media is as follows: SW=surface water, BC=rock scrapings from benthic cover.

1st Downstream Station after Outfall

Parameter[1]	Media[2]	Average	StDev	Count	LCI	UCI	Units
DO	SW	9.43	1.86	8	7.87	10.99	mg/L
Temp	SW	21.32	5.04	8	17.1	25.5	°C
pH	SW	7.55	0.25	8	7.34	7.76	Std units
Ammonia	SW	0.07	0.11	7	<DL	0.17	mg/L
Nitrate	SW	7.53	4.82	7	3.08	12.0	mg/L
TKN	SW	0.83	0.77	7	0.11	1.54	mg/L
OrthoP	SW	1.57	0.59	7	1.03	2.12	mg/L
Phosphorus	SW	1.44	0.64	9	0.95	1.93	mg/L
TSS	SW	1.67	1.00	7	0.75	2.60	mg/L
Chlorophyll-a	SW	3.09	1.47	7	1.73	4.44	µg/L
Pheophytin	SW	3.39	1.32	7	2.16	4.61	µg/L
Conductivity	SW	719.76	53.77	8	675	765	uS/cm
Phosphorus	BC	242.49	144.32	7	109	375	mg/ m^2
Nitrogen	BC	1444.20	788.43	7	715	2173	mg/m^2
Peri: Chloro	BC	126.29	44.18	7	85	167	Ratio
Periphyton	BC	10827.42	5757.91	7	5500	16,200	mg/m^2
Pheophytin	BC	30.10	17.11	7	14	46	mg/m^2
C:N Ratio	BC	1.41	0.43	6	0.96	1.86	Ratio
C:P Ratio	BC	18.72	6.30	6	12.1	25.3	Ratio
N:P Ratio	BC	13.81	2.19	7	11.8	15.9	Ratio
Pheo: Chloro	BC	0.33	0.15	7	0.19	0.48	Ratio
Mass:C	BC	6.66	1.85	6	4.72	8.60	Ratio
Chloro: Carbon	BC	0.06	0.04	6	0.02	0.11	Ratio
Periphyton Carbon	BC	1929.47	1131.34	6	742	3117	mg/m^2

1. The key to the abbreviated parameters is as follows: DO=dissolved oxygen, Temp = temperature, TKN= Total Kjeldahl Nitrogen, OrthoP= Orthophosphorus, TSS= Total Suspended Solids, Peri:Chloro=Periphyton to Chlorophyll-a Ratio, C:N Ratio = Carbon to Nitrogen Ratio, C:P Ratio = Carbon to Phosphorus Ratio, N:P Ratio = Nitrogen to Phosphorus Ratio, Pheo:Chloro=Pheophyton to Chlorophyll-a Ratio, Chloro:Carbon=Chlorophyll-a to Carbon Ratio.

2. The key to the abbreviated media is as follows: SW=surface water, BC=rock scrapings from benthic cover.

2^{nd} Downstream Station after Outfall

Parameter[1]	Media[2]	Average	StDev	Count	LCI	UCI	Units
DO	SW	13.51	4.06	8	10.1	16.9	mg/L
Temp	SW	23.34	7.01	8	17.5	29.2	°C
pH	SW	8.82	0.45	8	8.45	9.20	Std units
Ammonia	SW	0.04	0.04	7	<DL	0.08	mg/L
Nitrate	SW	5.81	5.18	7	1.02	10.6	mg/L
TKN	SW	0.97	0.53	7	0.48	1.46	mg/L
OrthoP	SW	1.10	0.66	7	0.49	1.71	mg/L
Phosphorus	SW	1.14	0.60	8	0.64	1.64	mg/L
TSS	SW	2.73	1.93	7	0.94	4.52	mg/L
Chlorophyll-a	SW	9.57	12.36	7	<DL	21.00	µg/L
Pheophytin	SW	6.76	6.03	7	1.18	12.33	µg/L
Conductivity	SW	660.38	68.88	8	603	718	uS/cm
Phosphorus	BC	611.21	782.94	7	<DL	1335.31	mg/m^2
Nitrogen	BC	1454.99	1103.54	7	434	2476	mg/m^2
Peri: Chloro	BC	214.77	233.16	7	-1	430	Ratio
Periphyton	BC	16548.46	23149.75	7	<DL	37958	mg/m^2
Pheophytin	BC	21.44	18.15	7	5	38	mg/m^2
C:N Ratio	BC	1.76	0.84	6	0.88	2.64	Ratio
C:P Ratio	BC	13.30	6.87	6	6.09	20.51	Ratio
N:P Ratio	BC	7.54	3.33	7	4.46	10.62	Ratio
Pheo: Chloro	BC	0.27	0.16	7	0.12	0.42	Ratio
Mass:C	BC	8.74	8.21	6	0.12	17.36	Ratio
Chloro: Carbon	BC	0.04	0.02	6	0.02	0.07	Ratio
Periphyton Carbon	BC	2240.66	1980.58	6	162	4320	mg/m^2

1. The key to the abbreviated parameters is as follows: DO=dissolved oxygen, Temp = temperature, TKN= Total Kjeldahl Nitrogen, OrthoP= Orthophosphorus, TSS= Total Suspended Solids, Peri:Chloro=Periphyton to Chlorophyll-a Ratio, C:N Ratio = Carbon to Nitrogen Ratio, C:P Ratio = Carbon to Phosphorus Ratio, N:P Ratio = Nitrogen to Phosphorus Ratio, Pheo:Chloro=Pheophyton to Chlorophyll-a Ratio, Chloro:Carbon=Chlorophyll-a to Carbon Ratio.
2. The key to the abbreviated media is as follows: SW=surface water, BC=rock scrapings from benthic cover.

Table A.2: Confidence Intervals of the Mean for San Gabriel-South Fork Sites

Upstream Station/ above Outfall

Parameter[1]	Media[2]	Average	StDev	Count	LCI	UCI	Units
DO	SW	9.14	1.88	7	7.41	10.9	mg/L
Temp	SW	22.32	7.58	8	16.0	28.7	^oC
pH	SW	8.12	0.20	8	7.95	8.29	Std units
Ammonia	SW	0.01	0.00	7	0.005	0.01	mg/L
Nitrate	SW	0.15	0.15	7	0.016	0.287	mg/L
TKN	SW	0.35	0.14	7	0.223	0.481	mg/L
OrthoP	SW	0.01	0.01	7	0.001	0.016	mg/L
Phosphorus	SW	0.01	0.00	8	0.007	0.013	mg/L
TSS	SW	1.40	0.59	7	0.858	1.94	mg/L
Chlorophyll-a	SW	1.00	0.54	7	0.496	1.50	µg/L
Pheophytin	SW	0.29	0.07	7	0.222	0.350	µg/L
Conductivity	SW	536.14	133.01	8	425	647	uS/cm
Phosphorus	BC	9.39	4.17	7	5.53	13.2	mg/ m^2
Nitrogen	BC	284.98	139.44	7	156.0	413.9	mg/m^2
Peri:Chloro	BC	338.56	241.64	7	115.1	562.0	Ratio
Periphyton	BC	4630.19	2731.10	7	2104	7156	mg/m^2
Pheophytin	BC	1.57	1.82	7	<DL	3.26	mg/m^2
C:N Ratio	BC	2.78	0.59	6	2.15	3.40	Ratio
C:P Ratio	BC	195.24	88.22	6	103	288	Ratio
N:P Ratio	BC	68.66	21.43	7	48.8	88.5	Ratio
Pheo:Chloro	BC	0.08	0.06	7	0.03	0.13	Ratio
Mass:C	BC	7.40	2.79	6	4.48	10.3	Ratio
Chloro: Carbon	BC	0.04	0.03	6	0.00	0.07	Ratio
Periphyton Carbon	BC	698.43	419.49	6	258	1139	mg/m^2

1. The key to the abbreviated parameters is as follows: DO=dissolved oxygen, Temp = temperature, TKN= Total Kjeldahl Nitrogen, OrthoP= Orthophosphorus, TSS= Total Suspended Solids, Peri:Chloro=Periphyton to Chlorophyll-a Ratio, C:N Ratio = Carbon to Nitrogen Ratio, C:P Ratio = Carbon to Phosphorus Ratio, N:P Ratio = Nitrogen to Phosphorus Ratio, Pheo:Chloro=Pheophyton to Chlorophyll-a Ratio, Chloro:Carbon=Chlorophyll-a to Carbon Ratio.
2. The key to the abbreviated media is as follows: SW=surface water, BC=rock scrapings from benthic cover.

1st Downstream Station after Outfall

Parameter[1]	Media[2]	Average	StDev	Count	LCI	UCI	Units
DO	SW	10.94	2.31	7	8.80	13.08	mg/L
Temp	SW	24.89	6.29	8	19.63	30.14	^oC
pH	SW	8.33	0.22	8	8.143	8.515	Std units
Ammonia	SW	0.03	0.05	7	<DL	0.069	mg/L
Nitrate	SW	0.25	0.17	7	0.092	0.411	mg/L
TKN	SW	0.39	0.12	7	0.279	0.503	mg/L
OrthoP	SW	0.02	0.02	7	0.001	0.032	mg/L
Phosphorus	SW	0.02	0.01	8	0.007	0.027	mg/L
TSS	SW	2.73	1.63	7	1.22	4.233	mg/L
Chlorophyll-a	SW	2.49	2.36	7	0.30	4.667	µg/L
Pheophytin	SW	0.90	0.71	7	0.242	1.558	µg/L
Conductivity	SW	490.79	50.73	8	448	533	uS/cm
Phosphorus	BC	107.68	75.84	7	37.5	178	mg/ m^2
Nitrogen	BC	915.46	592.11	7	368	1460	mg/m^2
Peri: Chloro	BC	393.37	581.33	7	-144	931	Ratio
Periphyton	BC	11491.05	8861.04	7	3300	19,700	mg/m^2
Pheophytin	BC	10.87	8.02	7	3.45	18.3	mg/m^2
C:N Ratio	BC	2.27	0.70	6	1.54	3.00	Ratio
C:P Ratio	BC	47.01	18.33	6	27.8	66.2	Ratio
N:P Ratio	BC	20.22	4.82	7	15.76	24.67	Ratio
Pheo:Chloro	BC	0.23	0.18	7	0.06	0.39	Ratio
Mass:C	BC	6.93	2.17	6	4.66	9.21	Ratio
Chloro: Carbon	BC	0.05	0.04	6	0.01	0.09	Ratio
Periphyton Carbon	BC	1894.21	1435.42	6	388	3400	mg/m^2

1. The key to the abbreviated parameters is as follows: DO=dissolved oxygen, Temp = temperature, TKN= Total Kjeldahl Nitrogen, OrthoP= Orthophosphorus, TSS= Total Suspended Solids, Peri:Chloro=Periphyton to Chlorophyll-a Ratio, C:N Ratio = Carbon to Nitrogen Ratio, C:P Ratio = Carbon to Phosphorus Ratio, N:P Ratio = Nitrogen to Phosphorus Ratio, Pheo:Chloro=Pheophyton to Chlorophyll-a Ratio, Chloro:Carbon=Chlorophyll-a to Carbon Ratio.

---

2. The key to the abbreviated media is as follows: SW=surface water, BC=rock scrapings from benthic cover.

2^{nd} Downstream Station after Outfall

Parameter[1]	Media[2]	Average	StDev	Count	LCI	UCI	Units
DO	SW	10.38	1.68	7	8.83	11.9	mg/L
Temp	SW	23.62	7.28	8	17.5	29.70	^{o}C
pH	SW	8.19	0.28	8	7.96	8.43	Std units
Ammonia	SW	0.01	0.00	7	0.005	0.012	mg/L
Nitrate	SW	0.14	0.15	7	0.002	0.287	mg/L
TKN	SW	0.30	0.12	7	0.190	0.419	mg/L
OrthoP	SW	0.01	0.01	7	0.001	0.016	mg/L
Phosphorus	SW	0.01	0.01	8	0.006	0.018	mg/L
TSS	SW	1.27	0.58	7	0.738	1.805	mg/L
Chlorophyll-a	SW	6.07	13.69	7	<DL	18.7	µg/L
Pheophytin	SW	2.04	4.48	7	<DL	6.19	µg/L
Conductivity	SW	483.65	46.40	8	445	522	uS/cm
Phosphorus	BC	21.34	13.15	7	9.18	33.5	mg/ m^2
Nitrogen	BC	560.71	264.82	7	316	806	mg/m^2
Periphyton:Chloro	BC	850.21	1104.79	7	-172	1870	Ratio
Periphyton	BC	12822.41	11530.15	7	2160	23,500	mg/m^2
Pheophytin	BC	3.35	3.11	7	0.47	6.22	mg/m^2
C:N Ratio	BC	2.49	0.66	6	1.79	3.18	Ratio
C:P Ratio	BC	174.14	105.66	6	63.3	285	Ratio
N:P Ratio	BC	72.65	39.01	7	36.6	109	Ratio
Pheophytin: Chlorophyl-a	BC	0.19	0.20	7	0.01	0.38	Ratio
Mass:C	BC	10.57	6.40	6	3.86	17.29	Ratio
Chlorophyll-a: Carbon	BC	0.02	0.02	6	0.01	0.04	Ratio
Periphyton Carbon	BC	1230.55	508.78	6	697	1765	mg/m^2

1. The key to the abbreviated parameters is as follows: DO=dissolved oxygen, Temp = temperature, TKN= Total Kjeldahl Nitrogen, OrthoP= Orthophosphorus, TSS= Total Suspended Solids, Peri:Chloro=Periphyton to Chlorophyll-a Ratio, C:N Ratio = Carbon to Nitrogen Ratio, C:P Ratio = Carbon to Phosphorus Ratio, N:P Ratio = Nitrogen to Phosphorus Ratio, Pheo:Chloro=Pheophyton to Chlorophyll-a Ratio, Chloro:Carbon=Chlorophyll-a to Carbon Ratio.

---

2. The key to the abbreviated media is as follows: SW=surface water, BC=rock scrapings from benthic cover.