Linking Chemical and Biological Monitoring Components in the TMDL Process

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Abstract

A TMDL for nutrients was initiated for the North Bosque River in central Texas in 1998. Monitoring associated with the TMDL effort has focused on nutrients due to their role in promoting excessive algae growth as indicated by elevated chlorophyll-a levels throughout the river. Because Texas has only narrative nutrient criteria, linkages between in-stream chlorophyll-a and nutrient concentrations were needed to develop quantifiable in-stream nutrient targets that would link these biological and chemical components. The technical challenge was in defining the limiting factor to algal growth and establishing a quantifiable nutrient target that was meaningful and feasible for control implementation. Algal bioassays indicated phosphorus to be the limiting nutrient within the river system. A number of different approaches were used for establishing relationships between phosphorus and chlorophyll-a concentrations for target development. An initial in-stream target of 0.03 mg/L PO_4-P using an annual average of monthly grab samples was proposed to achieve a chlorophyll-a level of about 20 µg/L. This target is being reviewed and a watershed-loading model (SWAT) is being applied to evaluate implications of management practices on the feasibility of meeting the proposed target.

Introduction

Water quality standards for the State of Texas as determined by the Texas Natural Resource Conservation Commission (TNRCC) indicate that the North Bosque River should be suitable for contact recreation, drinking water supply and a healthy aquatic ecosystem (TNRCC, 1996). Water quality assessments show high levels of nutrients contributing to excessive growth of algae within the river, which can impair the river's aesthetic value, potentially causes taste and odor problems in drinking water and result in fish kills under certain conditions

(TNRCC, 1999a). In response to nutrient conditions, classified segments 1226 (North Bosque River) and 1255 (the Upper North Bosque River) are on the Texas 303(d) list for development of Total Maximum Daily Loads (TMDLs). This TMDL process focuses on the control of elevated nutrient levels with the expected benefit of decreasing levels of algae. Although Lake Waco (Segment 1225), the receiving waterbody for the North Bosque River, is not currently on the 303(d) list, the stakeholder group is considering the water quality of the entire Lake Waco watershed within the TMDL process.

The North Bosque River is located in the Brazos River Basin as part of the LakeWaco watershed and originates in Erath County northwest of Stephenville (Figure 1). From Stephenville, the river flows from northwest to southeast by the towns of Hico, Iredell, Meridian, Clifton and Valley Mills before entering Lake Waco in McLennan County. The watershed covers about 781,000 acres (316,000 ha) stretching across the Cross Timbers and Prairies ecoregion with a small portion of the southeast end of the watershed occurring in the Blacklands ecoregion (Schuster and Hatch, 1990). The North Bosque River supplies surface water for the cities of Clifton and soon Meridian. While Lake Waco supplies water for the city of Waco and surrounding communities. Over 200,000 people use water originating from the North Bosque River as their primary drinking water source (TNRCC, 1999a). The North Bosque River also provides water for a variety of agricultural activities as well as some recreational opportunities, such as fishing, under normal flow conditions. North Bosque River flows can be quite variable, and the river's upper reaches are often dominated during late summer by municipal wastewater treatment effluent.

The TMDL process as a tool for implementing State water quality standards follows seven general steps (USEPA, 1998a). These include: 1) identifying the problem, 2) identifying the difference between desired and current conditions, 3) identifying the sources of impairment, 4) identifying controls to reduce impairment, 5) implementing controls, 6) monitoring for improvement and 7) revising the TMDL as justified by monitoring after controls are implemented. This paper will focus on target development within the North Bosque River TMDL effort for the control of excessive algae growth associated with accelerated eutrophication. The goal of the target is to sustain biological ecosystem integrity. Specific tasks include determining what limits the growth of algae within this system and developing predictive relationships between the limiting factor and algae production to identify feasible endpoints or targets for control efforts.

Within aquatic systems, eutrophication has multiple meanings. In scientific terms, eutrophication refers to the natural aging process of streams and lakes as sedimentation and loadings occur over time. In terms of evaluating water quality, eutrophication or more specifically cultural eutrophication refers to the human induced increase in the rate of the "aging process" of a lake or stream. When an overabundance of algae occurs in response to cultural eutrophication, a number of different potential impacts can occur. These include changes in the structure and diversity of the aquatic ecosystem with changes in algal populations and communities, periods of oxygen deficiency as respiration demands exceed oxygen production, increases in pH with changes in the carbonate-carbonic acid balance, decreases in water clarity and releases of toxins or other undesirable substances from certain species of algae, such as geosmin from *Oscillatoria chalybea* or MIB (2-methylisoborneol) from *Anabaena circinalis* (Izaguirre, et al., 1982). Some general references on the potential impacts of algal blooms on aquatic ecosystems include Laws (1993), Boyd (1990), Riemann and Søndergaard (1986), and Middlebrooks et al. (1973).

The level of nutrients and plant growth within a waterbody generally defines its trophic status. Categories for tropic state range from oligotrophic, referring to low productivity, to mesotrophic, eutrophic and hypereutrophic, referring to very high productivity. Trophic status is generally measured in units of chlorophyll-a (CHLA) in the water column (mass per unit volume) or on the stream bottom (mass per unit area) as a surrogate for primary productivity. CHLA levels associated with the various trophic state categories have been suggested for lakes (Carlson, 1977 and Wetzel, 1983) and for streams (Dodd et al., 1998; Table 1). The difficult problem in water quality assessment is defining the appropriate trophic state for a given waterbody and the factor or factors that can be controlled to limit the production of algae if a lower trophic status is desired. Some limits to the production of algae include nutrients, primarily nitrogen (N) and phosphorus (P), light availability, water residence time or "wash out", water velocity, substrate factors and grazer abundance. Where cultural eutrophication is a problem,

Figure 1. Lake Waco watershed and locations of selected sampling sites.

an overabundance of nutrients is almost always the cause. In freshwater systems, phosphorus is generally the limiting nutrient, while in marine or estuary systems, nitrogen is more often limiting (Gibson, 1997). The limiting nutrient may then indicate the potential factor for controlling eutrophication.

Table 1. Suggested chlorophyll-a concentrations (µg/L) in relation to trophic state of lakes and streams.

Trophic State	Lakes (Carlson, 1977)	Lakes (Wetzel, 1983)	Streams (Dodd et al., 1998)
Oligotrophic	<3	<3	<10
Mesotrophic	3-7	2-15	10-30
Eutrophic	7-55	10-500	>30
Hypereutrophic	>55	>500	

In the North Bosque River TMDL process, in-stream and laboratory bioassays were used to define the limiting nutrient within the system focusing on N and P. These bioassays along with in-stream water quality monitoring data were then used to develop predictive relationships for target development. Potential nutrient targets are proposed for limiting algae production as indicated by CHLA concentrations within the stream system.

Defining the Limiting Nutrient

Bioassays were run for the North Bosque River using two general methods to evaluate the limiting nutrient (N or P) to algal growth. The first used standard algal bioassay procedures as outlined by USEPA (1978) and APHA (1995) employing *Selenastrum capricornutum* Printz. In addition, a slight modification of this procedure was employed using native phytoplankton inoculum from Lake Waco. The standard algal bioassay procedure represented monthly trials over a two-year period for one site along the North Bosque River. This site was sampling site BO100 from the Texas Institute of Applied Environmental Research (TIAER) monitoring program and is located close to the mouth of the river near the city of Valley Mills. The standard algal bioassays were conducted at the Limnology Laboratory at Baylor University in Waco (Dávalos-Lind and Lind, 1999).

The second method used an in-stream periphytometer to measure *in-situ* nutrient limitations (Matlock et al., 1998). The in-stream periphytometer was deployed at five sites along the North Bosque River and at a reference site along Neils Creek, which feeds into the North Bosque River between the cities of Clifton and Valley Mills. Data collected represent three different time periods at each site as presented by Matlock and Rodriguez (1999).

Phosphorus was the element limiting growth of *S. capricornutum* and native phytoplankton for the North Bosque River as indicated from the standard algal bioassay evaluations (Table 2). The addition of nitrogen generally showed a very limited growth response, while the addition of phosphorus or nitrogen plus phosphorus produced very similar growth responses. The growth response of the native algae was generally less than that of the *S. capricornutum* indicating a potential adaptation of the *S. capricornutum* as a laboratory species to growth in a nutrient rich environment.

Table 2. Mean and standard deviation (n=25) of growth response to phosphorus and nitrogen additions (fluorescence of treatment minus control) for samples collected between December 1996 and November 1998 for North Bosque River site BO100 (Dávalos-Lind and Lind, 1999).

Treatment	*Selnastrum capricornutum*	Native Algae
P Addition	102 ± 85	36 ± 37
N Addition	3 ± 6	2 ± 6
N + P Addition	149 ± 84	46 ± 47

The periphytometer study in a similar fashion compared growth potential between a control treatment and nutrient added treatments (Table 3). In summary, all three trials at the reference site on Neils Creek indicated phosphorus as the limiting nutrient. The North Bosque River sites indicated phosphorus limitation more often than nitrogen limitation, although in this nutrient rich environment, the *in-situ* trials indicated that other factors, such as light limitation due to canopy cover, were more limiting to algal growth than either nitrogen or phosphorus.

Table 3. Summary of *in-situ* stream bioassay results (Matlock and Rodriguez, 1999).

Location	P-Limited	N-Limited	Co-Limited	Other	Total
North Bosque River Sites	4 (29%)	1 (7%)	2 (14%)	7 (50%)	14
Neils Creek (Reference Site)	3 (100%)	0 ----	0 ----	0 ----	3

Evaluating Phosphorus as a Response Variable to Algal Growth

With phosphorus as the limiting nutrient, four general approaches were used to develop a predictive relationship between in-stream phosphorus and CHLA concentrations for target development. The first considered TNRCC screening levels for CHLA. The second used reference site values as a way of setting a benchmark for ecosystem expectations related to a minimally impacted watershed. The third evaluated the relationship of *in-situ* productivity compared to maximum potential productivity, as measured through the periphytometer bioassay study, in relation to in-stream phosphorus concentrations. The fourth method evaluated annual mean CHLA versus phosphorus concentrations from routine grab sampling data from sites throughout the Lake Waco watershed based on a saturating nutrient concept for CHLA production.

In evaluating a target, orthophosphate-phosphorus (PO_4-P) was chosen as the independent variable driving algal productivity and growth for four reasons. Unlike total-P, PO_4-P is not confounded with the dependent variable of algal biomass as measured by CHLA. Secondly, PO_4-P has been shown to predict algal population growth rates according to an external-substrate model (Monod 1950; Kilham 1978). This "Monod" model has been well supported by a number of laboratory and field studies of algal population growth (see Grover 1997 for a review). Third, aquatic ecosystems enriched through cultural eutrophication are known to have elevated and measurable levels of PO_4-P. This is in contrast to less productive natural systems where ambient PO_4-P concentrations are very hard to measure (e.g., Dillon and Rigler, 1974). Finally, PO_4-P is the largest component of bioavailable phosphorus in the North Bosque River as measured by the Sharpely (1993) method.

Monitoring data from January 1996 through December 1999 collected at eight stream sites along the North Bosque River was compared to TNRCC screening levels for CHLA, PO_4-P and total-P (Table 4). While 49% of CHLA samples exceeded the screening level of 16.1 µg/L, only 9% of phosphorus samples exceeded either the PO_4-P or total-P screening level. This does not indicate that phosphorus is not a problem in the North Bosque River or that phosphorus is not related to CHLA production, but these results are an artifact of the methodology used by the TNRCC in setting screening levels. These screening levels represent the 85 percentile of all stream data for the State of Texas and do not indicate a biological linkage between phosphorus and CHLA concentrations (TNRCC, 1999b). As the State of Texas has not adopted numeric criteria for nutrients and CHLA, the TNRCC has developed this methodology for determining classified waters that may be of concern due to nutrient or CHLA levels. For reference, USEPA is forming a strategy for developing regional numeric criteria for nutrients, but this guidance is not yet available (USEPA, 1998b). It is important to note that the TNRCC screening levels are not static and may change as the TNRCC annually re-evaluates water quality within the State's waters.

Table 4. Percent and (number) of North Bosque River samples exceeding TNRCC screening levels.

North Bosque River Samples Evaluated	Screening Level (TNRCC, 1999b) CHLA 16.1 µg/L	PO_4-P 0.91 mg/L	Total P 1.21 mg/L
430	49 % (211)	----	----
767	----	9% (70)	----
764	----	----	9% (65)

In comparing reference site values on Neils Creek to values along the North Bosque River, a much lower mean CHLA and PO_4-P was indicated for Neils Creek (Table 5). A much larger variation in values was noted for values along the North Bosque. This variation, in part, is accounted for by spatial variation in sampling sites and flow along the North Bosque River from upstream to downstream sites. In general, the highest concentrations of CHLA and PO_4-P are found in the upper reaches of the North Bosque River with decreasing concentrations from upstream to downstream locations (McFarland and Hauck, 1998; Pearson and McFarland, 1999). Using Neils Creek as a reference site, a mean CHLA of 4 µg/L could be expected at a PO_4-P concentration of 0.014 mg/L as a benchmark within this ecoregion.

Table 5. Basic statistics for monthly CHLA and bi-weekly PO_4-P samples from eight monitoring sites along the North Bosque River compared to reference site data on Neils Creek for January 1996 through December 1999.

	CHLA (µg/L)					
	Mean	Median	Std	Min	Max	# Obs.
North Bosque	27	16	34	0.5	290	430
Neils Creek	4	3	3	0.6	15	48
	PO_4-P (mg/L)					
	Mean	Median	Std	Min	Max	# Obs.
North Bosque	0.34	0.10	0.61	0.002	4.51	767
Neils Creek	0.014	0.009	0.014	0.002	0.08	86

The third approach involved use of the Lotic Ecosystem Trophic Status Index (LETSI). The LETSI is defined as the ratio of baseline primary productivity (BPP) to maximum potential productivity (MPP) where BPP is represented by the control treatment containing no added nutrients and MPP is represented by the N plus P treatment from the periphytometer bioassay method (Matlock et. al., 1999). The LETSI should vary between zero and one with a value of one indicating that the stream is at MPP. LETSI values from the bioassay treatments were compared to in-stream PO_4-P concentrations at the time of the periphytometer trials (Figure 2). In Figure 2, sites BO020, BO040, BO070, BO090 and BO100 represent locations along the North Bosque River. BO020 is located just above Stephenville and BO040 is located below Stephenville about a quarter mile below the discharge for the Stephenville wastewater treatment plant. Site BO070 is located just north of Hico, while sites BO090 and BO100 are located near the cities of Clifton and Valley Mills, respectively. Also included in Figure 2 are sites HC060 on Hog Creek, MB060 on the Middle Bosque River and NC060 on Neils Creek. In relation to algal productivity, sites BO020 and BO040 were at nutrient saturated production or MPP. It appeared that saturation of baseline production occurred at a PO_4-P concentration of about 0.2 mg/L. Site HC060 also indicated nutrient saturation, but factors other than phosphorus were considered to limit production at site. NC060, our reference site, had a LETSI of 0.4 at a PO_4-P concentration of 0.015 mg/L. A Michaelis-Menten equation was fit to the data using the Lineweaver-Burk parameter estimation method to calculate the half saturation constant (Lehninger, 1975). The LETSI reaches 50% at a PO_4-P of 0.04 mg/L, which was considered a potential target value.

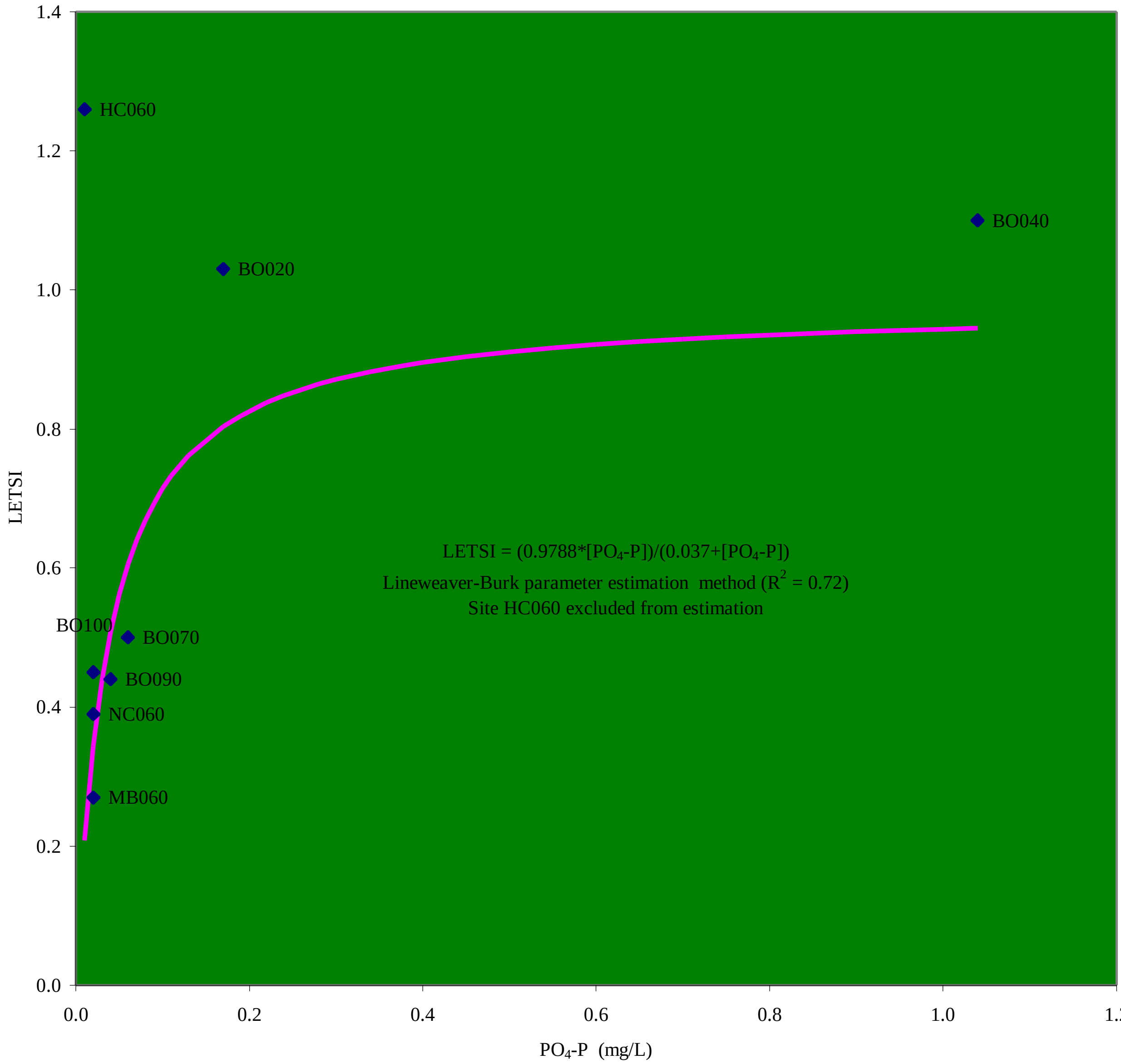

Figure 2. Average LETSI verses stream PO_4-P concentrations.

The fourth method used to relate CHLA to PO_4-P concentrations compared annual mean values of routine grab samples from sampling sites across the Bosque River watershed (Figure 3). A distinct break in the data was noted at a PO_4-P concentration of about 0.05 mg/L. Below 0.05 mg/L PO_4-P, CHLA concentrations were generally below 20 µg/L. Above 0.05 mg/L PO_4-P, mean annual CHLA concentrations appeared to plateau between 20 and 45 µg/L. In Figure 3, data from sampling site BO040 were excluded for clarity of presentation. At site BO040 on the North Bosque River, annual PO_4-P values ranged from 0.9 to 1.9 mg/L with annual CHLA concentrations generally greater than 20 µg/L.

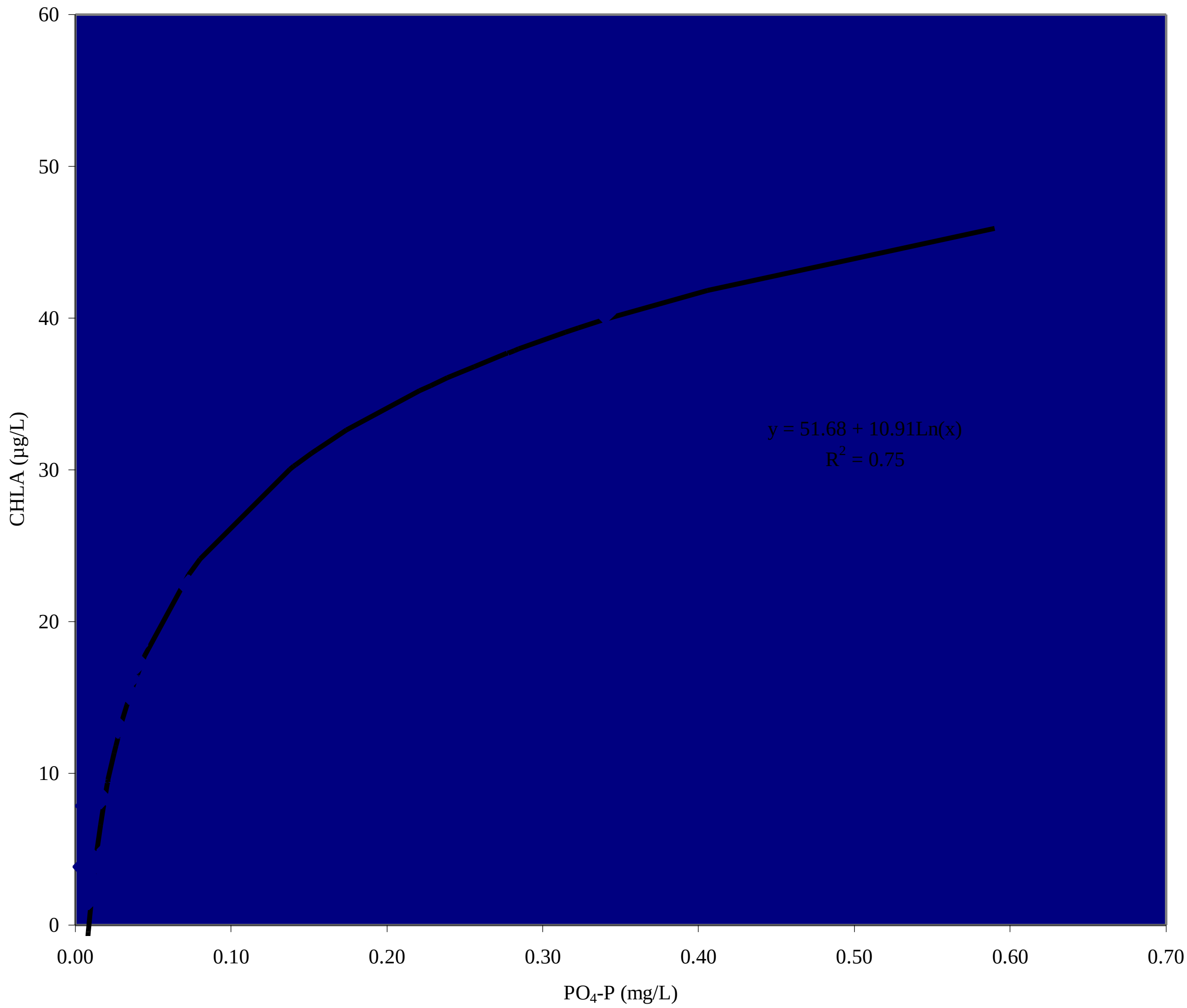

Figure 3. Comparison of annual average CHLA with PO_4-P concentrations.

A natural log function was fit to best describe the relationship between annual CHLA and PO_4-P concentrations. A PO_4-P concentration of 0.05 mg/L corresponded to a CHLA level of about 20 µg/L. For reference, a PO_4-P concentration of 0.038 mg/L corresponded to a CHLA level of 16.1 µg/L, the TNRCC screening level.

Summary of Potential Targets

From these relationships, a summary of potential PO_4-P targets was developed (Table 6) for presentation to the TMDL advisory committee and technical workgroup. These potential targets represent a preliminary analysis of the monitoring data for target development and should not be taken as a definitive analysis of the TMDL target for the North Bosque River. An initial target of 0.03 mg/L PO_4-P as an annual average for the North Bosque River at Meridian, Clifton and Valley Mills has been set. This target is being reviewed and a watershed-loading model (SWAT) is being applied to evaluate implications of management practices on the feasibility of meeting this proposed target.

Table 6. Summary of potential PO_4-P targets for controlling algal growth.

	PO_4-P	CHLA
Reference Site (NC060) –		
Mean Jan96-Dec99	0.014 mg/L	4 µg/L
Annual Mean	0.015 mg/L	4 µg/L
LETSI Productivity 50%	0.040 mg/L	Not Applicable
Annual Stream Data –		
Threshold Break	0.050 mg/L	19 µg/L
Mean at TNRCC CHLA	0.038 mg/L	16.1 µg/L
Range	0.014 – 0.05 mg/L	4-20 µg/L

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