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Nutrient Targets for Lake Waco and North Bosque River: Developing Ecosystem Restoration Criteria
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Nutrient Targets for Lake Waco and North Bosque River

Abstract

The State of Texas has identified a number of water bodies as having potential water quality problems as a result of nutrient enrichment from point and nonpoint sources (TNRCC, 1996). In the Bosque River watershed, elevated levels of chlorophyll-α (CHLA) and nutrients have prompted the state to classify portions of the watershed as water quality impaired, and to place selected water quality segments on the Clean Water Act Section 303(d) list. In response to the listing of the Upper North Bosque River (Segment 1255) and the North Bosque River (Segment 1226) and in cooperation with stakeholders in the basin, water quality monitoring data and in situ nutrient bioassays were used to develop nutrient targets by answering the following questions:

1. What nutrient or nutrients limit aquatic primary production in the watershed?
2. What functional relationship(s), if any, exists between the limiting nutrient and primary production?
3. How do degraded water bodies compare to reference sites?

A series of in situ stream bioassays were performed to develop a predictive relationship between nutrient supply and algal production and growth. Stream bioassays were performed using a recently developed periphytometer that supplies specific nutrient treatments to an artificial substrate (Matlock et al., 1998). The Matlock periphytometer is capable of estimating stream trophic status as the ratio of control production to nutrient saturated production. This ratio is referred to as the Lotic Ecosystem Trophic Status Index (LETSI). Individual glass-fiber filters were supplied with nitrogen (N), phosphorus (P), or N and P in combination and deployed in the stream in a replicated design to test for nutrient limitation in algal biomass production. Eight stream sites within the watershed were tested seasonally using this method. Growth and production responses to the treatments were estimated from CHLA production. Laboratory-based bioassays measured the algal growth potential of Lake Waco waters from three reservoir monitoring sites. Natural phytoplankton collected from the lacustrine area of the reservoir and Selenastrum capricornutum from laboratory cultures were used to measure the growth response to ambient nutrient concentrations as well as to additions of N, P, or N and P in combination. Soluble reactive P (PO₄-P) dose-response bioassays were performed in the lake once phosphorus was identified as the dominant limiting nutrient. Growth responses were assessed daily using in vivo fluorescence (IVF), and growth rates were determined by applying an exponential growth model to the IVF data. Bioassay results were compared to field data collected at two-week or monthly intervals at all of the bioassay sites. Comparisons were made between biomass production or algal growth rates and ambient nutrient concentrations.

Bioassay results indicated that aquatic primary production in the watershed was limited by phosphorus availability. For stream sites, over 40 percent of the in situ bioassays showed phosphorus limitation or co-limitation with nitrogen. In-stream primary production, measured as the ratio of control to nutrient sufficient production (aka LETSI), was a significant function of in situ P concentrations. North Bosque River sites showed a decrease of LETSI values as you moved downstream from site BO040 to BO100. Sites showing little or no P limitation (BO020 and BO040) had LETSI values very close to unity. For reservoir sites, over 90 percent of the bioassays showed phosphorus limitation. Dose-response bioassay experiments using P as the limiting nutrient established predictive relationships between phosphorus nutrient supply and experimental natural phytoplankton biomass. Maximum growth rate
estimates from these dose-response bioassays declined over an order of magnitude throughout the summer.

Stream and reservoir bioassay results were used to develop provisional nutrient targets by comparison of in situ and laboratory experimental data with contemporaneous monitoring data. Provisional nutrient targets were derived from maximum growth responses of both stream and reservoir algae to saturating nutrient supply and from half-saturation constants for reservoir algae population growth or biomass production. These provisional nutrient targets were compared to the results of other analyses. Additional targets were developed based upon statewide screening criteria for algal biomass and within-basin reference sites or historical averages.
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CHAPTER 1

Introduction

The Role of Nutrient Targets in Restoring Water Quality

Restoration of polluted aquatic ecosystems has been a topic of concern among aquatic ecologists since the 1970s. Early efforts to identify the causative agents of aquatic ecosystem degradation focused on the obvious impacts associated with accelerated eutrophication (sometimes referred to as cultural eutrophication) of lakes and reservoirs. Excessive loadings of nutrients and organic wastes from point sources into these water bodies were shown to enhance and promote algal growth, leading to the accumulation of algal biomass and to whole-scale changes in lake and reservoir metabolism. In response to these observations, numerous attempts were made to restore the affected water bodies through practical means, such as diversion of known point sources away from lakes and reservoirs (e.g., Edmondson 1972). At the same time, a number of research projects were initiated to define acceptable baseline nutrient conditions to serve as restoration endpoints for lake and reservoir managers. The most well known of these efforts was a literature and data review compiled by R. A. Vollenweider (1968) for the Organization for Economic Cooperation and Development (OCDE). His review concluded that the previously identified critical nutrient levels of 300µg/L inorganic nitrogen and 10µg/L inorganic phosphorus from the work by Sawyer (1947) were reasonable benchmarks for temperate lakes and reservoirs.

Vollenweider’s analysis affirming Sawyer’s recommendations initiated efforts to define appropriate nutrient management criteria for water quality impaired lakes and reservoirs based, in part, on mass-loading models. Numerous empirical relationships between average nutrient loads and in-lake nutrient concentrations were developed, leading to a series of published mass balance equations as well as statistical models capable of predicting algal biomass from nutrient loads (see Meeuwig and Peters 1996 for a review). The underlying assumption in these models was tested with a series of whole-lake fertilization experiments that provided dramatic evidence of nutrient limitation in general, and limitation by phosphorus in particular (Schindler, 1977), in freshwater lakes. With the fundamental importance of phosphorus affirmed by Schindler’s whole-lake experiments and by Vollenweider’s pattern analysis, restoration efforts turned towards building a more mechanistic understanding of the eutrophication process.

Similar efforts aimed at exploring the implications of nutrient enrichment in rivers and streams were initiated within the same time frame as the studies focused on lakes and reservoirs. The early work of Odum (1956) and King and Ball (1967) illustrated how stream productivity was enhanced by nutrient addition. Experimental manipulations involving nutrient additions to streams documented the role of phosphorus in limiting periphyton accumulation in streams (Stockner and Shortreed, 1976; Peterson et al., 1983) while work by Hornberger et al. (1977) developed methods to assess eutrophication potential using productivity (P) measurements and productivity to respiration ratios (P/R). Nutrient enrichment of experimental streams (Horner et al., 1983) provided estimates of critical phosphorus levels as well as algal biomass criteria indicative of eutrophy. According to Horner’s experiments, soluble reactive phosphorus (SRP) supply rates of 15 to 25µg/L
produced nuisance levels of periphyton biomass in excess of 150 mg chlorophyll-\(\alpha\) (CHLA)/m\(^2\). Maximum algal biomass for the same experiments was observed at supply rates between 50 and 80 µg/L SRP. These results are in general agreement with field-based estimates of critical total phosphorus levels for the filamentous alga *Cladophora*. Using maximum relative photosynthesis as the measure of growth and performance, Wong and Clark (1976) estimated the critical total phosphorus requirement at 60 µg/L.

Although these reports established a direct link between nutrient availability and eutrophication of streams and reservoirs, development of federal numeric water quality criteria for nutrients in freshwater did not take place. Despite the lack of federal criteria, a number of states moved forward to address eutrophication and adopted numeric phosphorus criteria for the protection of specific water bodies or classes of water bodies including streams and lakes. A 1988 summary of nutrient criteria found 13 states with some form of numeric criteria for phosphorus (USEPA, 1988). USEPA recently initiated an effort to develop ecoregion-based nutrient criteria for the entire United States (USEPA, 1998b). The underlying goal of this effort is to have numeric nutrient criteria adopted by the individual states as part of their respective water quality standards before 2003. Part of the motivation for this effort stems from the importance of nutrient enrichment as the suspected causative agent in water quality impairment across the nation. A 1998 assessment of the nation’s water quality identified nutrients as a major source of impairment to lakes and reservoirs as well as rivers and streams (USEPA, 2000). Forty-four percent of the impaired surface acres from lakes and reservoirs were attributed to nutrient pollution as were 29 percent of the impaired river and stream miles. In this same assessment, agricultural activities were identified as major potential sources of water quality impairment for 31 percent of impaired lake acres and 59 percent of impaired river miles (USEPA, 2000). No direct measure of the agricultural contribution to nutrient impairment was available from the EPA (2000) report, but basin-level studies of nutrient levels in streams and rivers from across the United States have identified significant associations between agricultural land uses and elevated nutrient concentrations (USGS, 1999). Results from the United States Geological Survey (USGS) National Water Quality Assessment (NAWQA) Program have documented significant increases in total phosphorus and total nitrogen concentrations in streams draining watersheds with high levels of agricultural and urban land uses. This result is not surprising as significant nutrient loading from agricultural sources has been documented since the late 1960s (e.g., Loehr, 1967). Systematic studies of the importance of agricultural nutrient loading to surface water (e.g., Lennox et al., 1997) and its management (e.g., Daniels et al., 1994; Pionke et al., 1997) have only recently become commonplace.

Resource managers must understand how land-use decisions interact with the specific characteristics of streams and reservoirs if they hope to reduce the number of aquatic ecosystems at risk for developing cultural eutrophication. Land-use based assessments of potential nutrient sources like those performed under the NAQWA program highlight linkages between activities in the watershed and the response of aquatic ecosystems to nutrient enrichment. Detailed studies of how land use affects nutrient loading for watersheds in Minnesota (Brezonik, personal communication), Wisconsin (Bennett et al., 1999) and Texas (McFarland and Hauck, 1999a&b) have pinpointed the specific role played by agriculture in elevating nutrient loads to streams and lakes. Current research on land use and its effect on the export of limiting nutrients to water bodies have highlighted the importance of integrated watershed management to implementing long-term solutions of cultural eutrophication. Preventing or reversing accelerated eutrophication associated with agricultural nonpoint source loading will require watershed-based solutions that address entire drainage basins.

Development of restoration targets is the first step in the restoration of basins with impaired water quality from excessive nutrient loading. The Lake Waco-Bosque River watershed is an example of a basin with water quality problems that stem from excessive nutrient loading.
from urban point sources and agricultural nonpoint sources. Previous studies have
determined that substantial point and nonpoint source loads of nitrogen (N) and phosphorus
(P) have elevated ambient concentrations of these two nutrients in the North Bosque River
and in Lake Waco (e.g., McFarland and Hauck, 1998a, 1998b, 1999a, 1999b). These elevated
nutrient levels are associated with increases in algal biomass (McFarland and Hauck 1998a,
1999a; McFarland et al., 2001), which has placed portions of the North Bosque River on the
State of Texas list of impaired water bodies.

Nutrient Enrichment in the Bosque River Ecosystem

The Lake Waco-Bosque River watershed encompasses 1,660 square miles in north central
Texas, all draining into Lake Waco (Figure 1). Major tributaries within the Bosque River
watershed include the North Bosque River, Hog Creek, Middle Bosque River and South
Bosque River, of which the North Bosque River basin covers about 74 percent of the total
drainage area.

From a regulatory perspective, the classified stream segments in the watershed are segments
1226 (North Bosque River), 1246 (Middle Bosque and South Bosque River), and 1255 (Upper
North Bosque River). Lake Waco is classified segment 1225 of the Brazos River Basin. Segment
1225 includes Lake Waco dam to the North Bosque River arm in McLennan county to the
confluence of the Middle Bosque River on the South Bosque River arm in McLennan county.
Segment 1226 includes the North Bosque River from Lake Waco, up to a point immediately
above the confluence of Indian Creek. Segment 1255 includes the North Bosque River from
Indian Creek to the confluence of the North Fork and South Fork above Stephenville. Segment
1246 includes the Middle and South Bosque Rivers located in McLennan county, as well as a
small portion of the Middle Bosque in Coryell county up to the confluence of Cave Creek and
Middle Bosque River. The state of Texas has designated the following uses for these four
classified segments (TNRCC, 1996):

Segment 1225 (Lake Waco)
- Contact recreation
- High aquatic life
- Public water supply

Segment 1226 (North Bosque River)
- Contact recreation
- High aquatic life
- Public water supply

Segment 1246 (Middle Bosque and South Bosque River)
- Contact recreation
- High aquatic life

Segment 1255 (Upper North Bosque River)
- Contact recreation
- Intermediate aquatic life

The two North Bosque River segments (1226 and 1255) are also included on the State of Texas
the Section 303(d) list. Nutrient enrichment in the form of elevated nutrient concentrations
and excessive algal growth is the major reason for the listing of these classified segments comprising the North Bosque River.

**Figure 1** Lake Waco-Bosque River Watershed with boundaries of classified water segments.

The Texas Institute for Applied Environmental Research (TIAER) has been performing water quality monitoring in the Lake Waco-Bosque River watershed since the early 1990s. Until 1996, the monitoring was focused on the watershed above the North Bosque River at Hico, Texas, and in that year the monitoring was expanded to the entire watershed. The monitoring has focused on sample collection during base flow and storm events on tributaries and rivers, measurement of stream flow at several sites, sample collection in Lake Waco, and sample analysis for nutrient forms and related constituents, such as total suspended solids, dissolved oxygen, and chlorophyll-a. Additional information on the monitoring program may be found in journal articles, e.g., McFarland and Hauck (1999a, 2001), and technical reports, e.g., McFarland and Hauck (1998a, 1998b, 1999b). Principal sampling site locations are described in Appendix A. The monitoring program is further described in semiannual data analysis reports to the Texas Natural Resource Conservation Commission, e.g., Pearson and McFarland (1999).

Analysis of TIAER monitoring data largely corroborates the section 303(d) listing of the two segments of the North Bosque River and provides additional insight into nutrient enrichment issues in the entire watershed. By first grouping sites by location in classified water body
segments, the monitoring data from June 1993 through May 1998 were analyzed according to protocol in TNRCC (1998) to provide an assessment of water quality parameters associated with nutrient enrichment. The assessment parameters include dissolved oxygen (DO), nitrite-nitrogen plus nitrate-nitrogen (NO₂-N+NO₃-N), ammonia-nitrogen (NH₃-N), dissolved reactive phosphorus (PO₄-P), total phosphorus (total-P), and chlorophyll-α (CHLA). In this assessment data collected from riverine automated samplers during storm water flows were analyzed separately from samples collected by routine grab sampling. Based on the percentage of data exceeding numeric water quality criteria (TNRCC, 1998), each parameter was assessed as fully supporting (FS), partially supporting (PS), or not supporting (NS) the numeric criterion. Texas has responded to the lack of numeric criteria by using nutrient screening levels derived from statistical distributions of statewide water quality monitoring data for specific categories of surface water (TNRCC, 1998). Screening levels exist for all water quality nutrient parameters reported in Table 1, and the percentage of data exceeding a screening level was assessed for each parameter as no concern (NC), potential concern (PC) or concern (C).

The assessment of TIAER data indicated that suspended algae (CHLA) were a concern in Lake Waco and both North Bosque River segments (Table 1). The various nutrient forms were assessed as being a concern or potential concern in some segments, and DO was assessed as a partially supporting in the Upper North Bosque River. This assessment indicates nutrient enrichment is a water quality issue in the North Bosque River and Lake Waco.

Table 1 Comparison of classified segments to TNRCC (1998) screening criteria. Results of comparing TIAER water quality data to TNRCC (1998) segment-specific criteria or screening level. FS = fully supporting; PS = partially supporting; C= concern; PC = potential concern; NC = no concern

<table>
<thead>
<tr>
<th>Segment</th>
<th>Sample Type</th>
<th>DO</th>
<th>NO₂-N+NO₃-N</th>
<th>NH₃-N</th>
<th>PO₄-P</th>
<th>Total-P</th>
<th>CHLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Waco (1225)</td>
<td>Surface</td>
<td>FS</td>
<td>C</td>
<td>NC</td>
<td>NC</td>
<td>PC</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Grab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Bosque (1226)</td>
<td>Grab</td>
<td>FS</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Storm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle &amp; South Bosque (1246)</td>
<td>Grab</td>
<td>FS</td>
<td>C</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
</tr>
<tr>
<td></td>
<td>Storm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper North Bosque (1255)</td>
<td>Grab</td>
<td>PS</td>
<td>C</td>
<td>PC</td>
<td>PC</td>
<td>PC</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Storm</td>
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</table>

The outcome of the analysis presented in Table 1 coupled with the section 303(d) listing for the North Bosque River indicate that excessive amounts of nutrients and suspended algae exist in the North Bosque River and Lake Waco. These and other problems prompted the listing of the North Bosque River as a nonpoint source impaired water from nutrient loadings (TNRCC and TSSWCB, 1999).

This report presents the results of an effort to develop numeric nutrient targets for the North Bosque River and Lake Waco. The purpose of nutrient target development is to provide restoration endpoints in the North Bosque River and Lake Waco for the USDA Lake Waco-Bosque River watershed Initiative Project. Attaining these endpoints should reduce the occurrence of algal blooms and long-term average concentrations of algae.
initiative, research efforts are being conducted to address several aspects of nutrient enrichment, its impacts, and its control. Further a stakeholder group, the Bosque River Advisory Committee (BRAC), which is comprised of various concerned citizens of the watershed, has been instrumental in development of the nutrient targets. Equally important in target development has been the Technical Work Group that provides technical overview of the initiative monitoring program and serves in an advisory role to the BRAC.
CHAPTER 2

Target Development

Restoration Targets for Eutrophic Water Bodies

Fundamental Basis of Reservoir Targets

The long history of lake eutrophication research has provided a wealth of theoretical, experimental, and applied investigations into how lakes and reservoirs respond to nutrient enrichment. For example, numerous simple mass-balance models have been derived from statistical descriptions of reservoirs and lakes of different trophic status (see Meeuwig and Peters, 1996, for a review). The most sophisticated of these approaches have been used to derive restoration endpoints for severely impaired water bodies (e.g., Lathrop et al., 1998). However, in order to develop these models or to use them to predict reservoir responses to changes in loading, very large data sets are required. In the early development of the loading models, Vollenweider (1976) used data from a modest sample of lakes and reservoirs to develop a predictive relationship between phosphorus loading and average summer algal biomass measured as chlorophyll-α (CHLA). Through numerous refinements and improvements to Vollenweider’s simple mass-balance model by a large number of authors (e.g., Meeuwig and Peters, 1996), larger and larger data sets have been used to explore the predictive capabilities of these statistical mass-balance models. Analysis of a large set of North American lakes by Smith and Shapiro (1981) found that the predictive capabilities of these statistical mass-balance models were acceptable for understanding how the average lake might respond to a given level of loading, however, specific lakes were found to be capable of individualistic responses to changes in nutrient loading. Inter-annual variability in the CHLA-nutrient load relationship was great enough in some lakes to call into question the usefulness of statistical, mass balance models for management purposes. In response to the shortcomings of simple mass-balance relationships, more complex, mechanistic mass-balance models were developed that included food-web components and consumer-resource interactions (e.g., Canale, DePalma, and Vogel, 1976; Larsen, Mercier, and Malueg, 1974). These efforts culminated in the production of mechanistic water quality models like WASP (DiToro, Fitzpatrick, and Thomann, 1983) and CE-QUAL-W2 (USACOE, 1986) capable of modeling lake and reservoir ecosystems. The two approaches illustrate the trade-off inherent in modeling strategies between generality and precision (Levins, 1966). Despite the loss in precision associated with simple nutrient loading-algal biomass models, they continue to be used as management tools.

The usefulness of simple, statistical mass-balance models to target development for a specific lake or reservoir is limited by two factors. The first is the size of the database required to apply the model to an individual lake and the time and expense required to collect the information. Five to ten years of focused monitoring may be required to establish a reliable productivity-nutrient loading relationship for a reservoir. This amount of time and effort may not be available if previous monitoring data have indicated that excessive nutrient loading is already occurring. Water quality managers may have limited time or funds available to collect new information. The second factor is the lack of specificity and precision in the underlying cause
and effect relationship between the target variable (e.g., CHLA) and the water quality parameter to be controlled (e.g., phosphorus) in these models. This detailed linkage is required to ensure the proposed target is relevant to the goal of maintaining or restoring water quality for the water body of concern.

**Fundamental Basis of River Targets**

Riverine eutrophication research faced similar challenges in the 1970s, but the initial solutions developed to meet these challenges differed from those that developed for lakes and reservoirs. Up until the late 1960s, mathematical models of river ecosystems focused on dissolved oxygen mass balance (Sandoval, Verhoff, and Cahill, 1976). Early work like that of Chen (1970) introduced the concept of mass balance approaches for elements other than oxygen. By 1972, modelers were incorporating the effects of nutrients into models of river systems as part of a generalized mass balance approach to predicting riverine responses to nutrient enrichment (Chen and Orlob, 1972; Sandoval, 1974). By 1976, this procedure was commonplace. Further model development through the 1970s and 1980s produced standard water quality simulation models like WASP (DiToro, Fitzpatrick, and Thomann, 1983) and CEQUAL-W2 (USACOE, 1986). These advanced models included explicit functional relationships between nutrient availability and phytoplankton growth and could be applied to reservoirs and lakes as well as rivers and estuaries. These more complex models unified the water quality modeling framework for freshwater ecosystems, but differences in the way these models were applied remained. Although rivers tended to be evaluated using complex models, the data required to run simulations were extensive. In addition to the data requirements, the need to test the specific assumptions inherent in these complex models was also prohibitive because of the time and effort involved.

The common solution to this problem was and still is the extensive use of calibration and verification data sets (Thomann and Mueller, 1987). By using a calibration data set to develop a hypothetical model of complex riverine ecosystems, modelers side-step the need to test each specific mechanism in the model proper. This approach works well to predict short-term dynamics of riverine systems but can fail to predict long-term dynamics. For example, the Potomac Estuary Model was unable to predict the magnitude of a massive algal bloom in 1983. Despite this failure, the model was an important investigative tool in determining the most likely cause of this bloom (Thomann and Mueller, 1987).

**Assumptions of Mass Balance Models**

What steps need to be taken to ensure the target is relevant to the goal? In the case of eutrophication associated with excessive phosphorus loading, additional data are required to establish how phosphorus reductions or other planned management actions will affect productivity. Additional information may be necessary to be certain that reducing phosphorus loads will decrease algal productivity on an acceptable time schedule and with an acceptable level of confidence in the predictive statistical relationship or mathematical function. Even when precise models are used, they may fail to make accurate predictions when specific assumptions are not met. In the case of nutrient target development, an assumption is made that the target parameter will track the water quality variable of interest (e.g., algal biomass). If this assumption is not met, the target parameter (e.g., phosphorus) is not relevant to the process of restoring water quality in the water body of interest.

One approach to addressing both of these concerns is to apply the tenants of resource-consumer theory as it relates to algae (Tilman, 1982; Grover, 1997) to the problem of endpoint definition. While nutrient resources such as nitrogen and phosphorus are consumed by all
algae, algal growth, and therefore algal biomass accumulation, must be controlled by nutrient supply rates before algal populations are in fact nutrient limited. Nutrient limitation, or control, of algal biomass accumulation is an assumption and prerequisite of all nutrient loading models that seek to predict algal biomass, or its surrogate, CHLA. Nutrient limitation is also an inherent assumption of any attempt to restore a highly productive water body through control of nutrient loading. Therefore, it is critical to restoration efforts to know that nutrients limit algal growth and biomass accumulation, and it is also necessary to know which nutrient is limiting to growth so that appropriate management action plans can be developed.

Once it has been established that a specific nutrient limits algal growth, further work must establish the functional relationship between increases in algal population size and external nutrients. Current understanding of nutrient-limited algal growth and reproduction suggests this functional relationship is the culmination of a two step process: nutrient uptake followed by cell division. Although two-step algal growth models are available (e.g., Kilham, 1978), simpler models exist that relate external nutrient concentrations directly to population growth (Monod, 1950). The Monod function has been useful in describing the nutrient-dependent growth of algae in culture and in predicting the outcome of nutrient competition (Tilman, 1982). More importantly, it is the only available model that predicts population growth rate based solely upon the external concentration of the limiting nutrient. This makes the Monod model a much more simple, if somewhat less reliable, alternative than a two-step growth model when dealing with natural algae communities (Grover, 1997). Despite its limitations, the Monod model has been incorporated into most mechanistic water quality models like CE-QUAL-W2 (Cole and Buchak, 1995) as an algal-growth subroutine.

Identifying the limiting nutrient and using the Monod model to predict algal growth responses to the supply rate are the first two steps in establishing a recovery objective for the water body of interest or in modeling the water body’s response. A third condition is field evidence that the water quality variable of interest, in this case algal biomass measured as CHLA, responds to changes in the loading or supply rate of the limiting nutrient. For example, in a phosphorus-limited system, correlation between annual total phosphorus (total-P) load, annual-average spring orthophosphate (PO₄-P) concentration, or annual-average growing season total-P and CHLA would provide evidence in support of the functional relationship between the potential target variable (e.g., total-P load) and the water quality parameter of interest (CHLA).

In the context of cultural eutrophication, re-establishing ecosystem function is best thought of as restoring natural biogeochemical cycling of nutrients and carbon. Simply put, this means reducing productivity to levels produced by background nutrient loading associated with minimal human impact. Unfortunately, historical data are often inadequate for this task, making the development of a target that meets this standard difficult. In the Lake Waco-Bosque River watershed, historical data do exist but these data are generally inadequate to the task of applying simple models for reservoirs such as those developed by Vollenweider or complex models for rivers and reservoirs like CE-QUAL-W2. Data simply do not exist for enough years and in sufficient detail to estimate the annual average response of algal biomass to changing levels of annual loading. In response to the lack of adequate data, an alternative approach to mass-balance productivity models was followed to develop nutrient restoration targets. The following series of tasks were performed to achieve the objective of nutrient target identification for both Lake Waco and the North Bosque River:

- Determine what nutrient limits algal biomass production
- Develop predictive relationships between algal biomass measure and putative target variable
- Identify reference conditions for feasible endpoints or targets
Nutrient Targets for Lake Waco and North Bosque River

Lake Waco Restoration Targets

Determining Limiting Nutrient

The first task was accomplished by performing a series of algal growth bioassays following standard EPA bioassay methods (APHA, 1995). Standard algal bioassays were conducted at the limnology laboratory at Baylor University in Waco (see Dávalos-Lind and Lind, 1999). These bioassays were similar in design to experiments performed in other Texas reservoirs to determine nutrient limitation patterns (e.g., Sterner, 1994). Bioassay methods and the detail of their application to Lake Waco sites are available elsewhere (Dávalos-Lind and Lind, 1999; McFarland et al., 2001). Growth responses of a native phytoplankton community from Lake Waco site LW013 (Figure 2) and a standard bioassay species Selenastrum capricornutum Printz. were assessed during the bioassays. Nitrogen and phosphorus were added separately and in combination to water collected at three Lake Waco sites (LW013 near the dam, LW015 near the State Highway 6 bridge, and LW070 near the Bosque Bend Clubhouse in Speegleville I Park) to test for nutrient-dependent growth. Growth of algal biomass in nutrient addition treatments was compared to results for control groups with no added nutrients. Bioassays were run at least once a month from December 1996 to November 1998. All bioassays used an acclimated growth rate method and tracked changes in biomass using in vivo fluorescence (IVF) of CHLA. Results from the three Lake Waco sites strongly indicate that phosphorus limits algal biomass growth during the study period (Table 2). Ninety-four percent of the experiments show some level of phosphorus limitation, with 92 percent showing only phosphorus limitation. All phosphorus was added as orthophosphate (PO4-P).

Developing a Predictive Relationship

The nutrient-limitation bioassay data clearly illustrate the importance of phosphorus to algal population growth and biomass accumulation. However, this importance does not establish a functional relationship between in-lake phosphorus concentration or some other measure of availability of the limiting nutrient and algal growth or productivity. To test for this relationship, a second set of bioassays were performed during 1998 to test the predictive capabilities of the Monod model. Native phytoplankton communities from lake site LW013 were subjected to an enrichment PO4-P gradient in the laboratory to establish a dose-response relationship. Each treatment group was enriched with a specific concentration of phosphorus as PO4-P, the presumptive limiting nutrient. PO4-P was added because measurements of Lake Waco and Bosque River bioavailable phosphorus (Sharpley, 1993) were dominated by PO4-P measured as soluble reactive phosphorus (TIAER, unpublished data).

Biomass-based algal growth rates were calculated using a simple exponential growth model. Details of this analysis are available in McFarland et al. (2001). Growth rate data were fit to a Monod function shown below using the SAS statistical package.

\[ \mu = \mu_{max} \cdot \frac{S}{(K_s + S)} \]

In the Monod model, observed growth rate (\(\mu\)) is a function of the maximum nutrient sufficient growth rate (\(\mu_{max}\)), the external nutrient concentration (\(S\)), and the half-saturation constant for growth (\(K_s\)). For the Lake Waco bioassays, resulting growth rates were reported on a per day basis (day\(^{-1}\)), and \(S\) and \(K_s\) were in \(\mu g/L\). The resulting Monod curves were significant for all spring and summer months, April through August, as well as for September.
Comparisons between $K_s$ estimates from all of the dose-response experiments reveal a strong seasonal decline between May and September (Figure 4).

**Figure 2** Location of major sampling sites in Lake Waco.

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**Table 2** Summary of Lake Waco bioassay results: December 1996 to November 1998. Summary of algal growth potential results for native algae communities (native) and *Selenastrum capricornutum* Printz. Ninety-four percent of all of the replicated bioassays exhibit some level of phosphorus limitation.

<table>
<thead>
<tr>
<th>Population</th>
<th>P-Limited</th>
<th>N-Limited</th>
<th>Co-Limited</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native</td>
<td>71</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>Selenastrum</td>
<td>67</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>Totals</td>
<td>138</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>Percent</td>
<td>92</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 3 Lake Waco bioassay dose-response curves. Examples of dose-response curves for natural phytoplankton communities collected at site LW013 in Lake Waco. Monod model parameter estimates and function are illustrated for an early (May) and mid-growing season (July) experiment. Maximum growth rates ($\mu_{\text{max}}$) and half-saturation constants ($K_s$) were estimated using the SAS statistical program.

3a. Lake Waco bioassay results from May 17, 1998

![Graph showing dose-response curve with Monod parameters: $K_s = 31.01$, $\mu_{\text{max}} = 2.25$.]

3b. Lake Waco bioassay results from July 1, 1998.

![Graph showing dose-response curve with Monod parameters: $K_s = 27.82$, $\mu_{\text{max}} = 0.86$.]

PO$_4$-P-based maximum growth rates show a slightly altered pattern, with elevated values in May and November and a flat response in the intervening months. The maximum growth rate in May was much larger than in September, which appears to be a transition month away from PO$_4$-P limitation. Unlike September, October data do not conform to a Monod function, while November again demonstrates a significant relationship between PO$_4$-P as the limiting nutrient and algal biomass.
Figure 4 Lake Waco bioassay results: Monod parameters.
Monod parameter estimates for dose-response bioassays of natural phytoplankton communities from LW013 in Lake Waco, which include phosphorus-dependent $\mu_{\text{max}}$ and $K_s$. $K_s$ decreases over the course of the summer, indicating nutrient uptake rates increase while growth rates decline.

The dose-response bioassays have shown that PO$_4$-P elicits a population growth effect consistent with the Monod algal growth model. Using $K_s$ as a benchmark, and assuming that algal population growth rate and algal biomass accumulation rate are directly proportional in Lake Waco, it is possible to identify an ambient PO$_4$-P concentration that will reduce current algal biomass by up to 50 percent. Scaling the result of each bioassay-derived Monod curve to $\mu_{\text{max}}$ and plotting the results on one graph makes it possible to derive a composite Monod function for the family of growth-rate curves produced by the bioassays. Applying the Monod model to the relative growth data in Figure 5 results in a composite $K_s$ for relative growth of 28µg/L.

Upon further inspection, some additional patterns emerge from the bioassay results. The strong seasonal decrease in $K_s$ suggests an increase in the competitive ability for PO$_4$-P among the algae community. However, there appears to be a trade-off between this increase in efficiency of nutrient-dependent growth and maximum attainable biomass growth rates (Figure 4). This trend could reflect a change in species composition, species-specific nutrient limitation, average cell size, or a combination of all three alternatives.

Lake Waco Target Estimates From Bioassay Data

In contrast to the majority of conventional statistical models that predict CHLA from total-P concentrations (Meeuwig and Peters, 1994), PO$_4$-P appears to be the controlling variable in this system. McFarland et al. (2001) have documented high phosphorus loading to the Lake Waco system during 1996-1998. A large portion of this load entered the lake as PO$_4$-P, and subsequent nutrient dynamics maintained a large pool of this phosphorus species. Unlike most low to moderately productive lakes (e.g., Dillon and Rigler, 1974), the PO$_4$-P pool in Lake Waco was generally indicative of instantaneous bioavailable phosphorus during this time.
period. The predictive relationship developed from the dose-response bioassay can be used to identify nutrient targets based on the importance of this $PO_4$-P pool in Lake Waco. For example, a target designed to reduce relative algal growth rate by 50 percent can be developed using $K_s$ as a benchmark. A composite $K_s$ value from relative growth rates gives a potential nutrient target of 28 $\mu$g/L $PO_4$-P for Lake Waco (Figure 5). Under the assumptions of the Monod model as applied under resource-consumer theory, this target approximates the nutrient supply that would sustain the selected 50 percent relative growth rate.

**Figure 5** Lake Waco $PO_4$-P dose-response experiments, 1998. Relative growth rates for $PO_4$-P dose-response bioassays. Monod fit ($\mu_{rel}$) to entire relative growth rate data set yields a $K_s$ of 28 $\mu$g/L.

The time period over which this target can be applied is also a point of concern. Given that the $K_s$ for relative growth rate was derived from bioassays performed over the entire growing season, it appears reasonable to apply the target to an average condition over the same time period. Furthermore, estimates of average nutrient supply rates in lakes and reservoirs may be approximated by early growing season average concentrations (e.g., Linsley Pond in 1938 reported by Hutchinson, 1944; Shagawa Lake in 1972 reported by Larsen, Mercier, Malueg, 1974). Models of average summer algal biomass have been based on total nutrient concentrations at spring turnover in north temperate lakes (Dillon and Rigler, 1974) and in Florida lakes (Baker, Brezonick, and Kratzer, 1981). Results from a CE-QUAL-W2 simulation for Lake Waco have documented a significant relationship between mean summer $PO_4$-P concentrations and mean summer CHLA concentration ($R^2 = 0.71; p < 0.05$; Flowers et al., in prep.).

Assuming this relationship is appropriate for Lake Waco, this target should be evaluated as a seasonal annual average $PO_4$-P concentration. Limitations of this target include the assumption that the supply rate of $PO_4$-P to summer algal populations is predicted by average ambient nutrient concentration over the same period. The impact of internal resupply of nutrients on algal biomass accumulation must also be reflected through changes in the seasonal average concentration of $PO_4$-P.

Other bioassay results are also useful in developing potential nutrient target values for Lake Waco. Results from the nutrient bioassays can be combined with monitoring data to establish a reference condition for nutrient-dependent biomass accumulation. Figure 6 shows the relationship between the relative maximum biomass from the bioassay control groups and $PO_4$-P concentrations from Lake Waco. $PO_4$-P data were collected along temporal and spatial nutrient gradients in Lake Waco, with sampling occurring at least monthly over a two year period at three locations. The relationship in Figure 6 establishes how biomass accumulation, measured in the control treatments from the bioassays, are a function of in-lake $PO_4$-P.
concentrations. The lowest observed biomass accumulation occurs within a range of minimum PO$_4$-P concentrations, suggesting a potential reference condition. Figure 6 illustrates that a clear threshold in maximum biomass production response to increasing nutrient availability occurs at 16µg/L PO$_4$-P. Below this level, algal biomass does not significantly respond to increasing PO$_4$-P concentrations. Above this level, biomass becomes elevated in response to increased availability of the limiting nutrient.

**Figure 6** Lake Waco bioassay productivity ratio as a function of in-lake PO$_4$-P concentration. Relative maximum biomass for control treatment from nutrient bioassays as a function of in-lake PO$_4$-P concentrations. Simple linear regression is significant at p<0.05. Dashed line at 16µg/L PO$_4$-P identifies hypothesized threshold for PO$_4$-P stimulation of algal growth. Biomass measured as in vivo fluorescence (IVF) units.

Biomass responses above the 16µg/L threshold are also much more variable, suggesting the increasing importance of additional controlling factors at higher ambient concentrations. This threshold response provides a second potential nutrient target of 16µg/L PO$_4$-P. A simple linear regression provides a significant estimate of how the bioassay control growth rates changed as a function of in-lake phosphorus availability, but the linear trend explains less than 30 percent of the variation in biomass response. Targets could be derived from the regression relationship, but the threshold response appears to provide a stronger alternative. Using the bioassay data and recognizing seasonal effects, it appears that two targets can be suggested: a composite $K_s$ from bioassay work yielding 28µg/L PO$_4$-P and a 16µg/L PO$_4$-P from threshold growth response found within lab monitoring (Table 3).

**Lake Waco Target Estimates From Monitoring Data**

Bioassays were used to identify the limiting nutrient and to develop predictive relationships between the limiting nutrient and algal biomass. Unfortunately, bioassays are not a direct measure of Lake Waco's response to changes in nutrient loading or in-lake nutrient supply rates. Furthermore, bioassays of this type may not account for complex limitation patterns (Sterner and Grover, 1998). Direct analysis of lake monitoring data will test for further associations between these variables and confirm the functional relationship between the presumptive limiting nutrient and our water quality response variable, CHLA. As discussed earlier, limited historical data prevent the application of mass-balance loading models to Lake Waco as a whole, however, it is possible to construct a predictive relationship between in-lake
algal biomass and in-lake phosphorus concentrations using data for each station averaged by year. For this analysis, average summer PO$_4$-P concentrations were calculated for the spring-summer growing period of April through September by year for each sampling site in the lake (Sterner, 1994; Lathrop et al., 1998). Simple linear regression analysis was performed on these calculated mean values for all years and sites. A more restricted analysis was also performed for sites near the dam because of their proximity to the City of Waco drinking water supply intake. The specific dam sites were chosen a priori based upon the segmentation schematics for application of the CE-QUAL-W2 reservoir model (see Flowers et al. In prep). Subsequent statistical analysis has suggested that these dam sites are not significantly different from a number of open lake sites (McFarland et al., 2001). However, the original analysis as presented to the Technical Workgroup and the Bosque River Advisory Committee in winter and spring of 1999 has been preserved for this report.

Table 3 Potential nutrient restoration targets for Lake Waco.
Potential nutrient targets to be used as a restoration criteria and their sources. All targets are in terms of average annual summer values as defined in the text.

<table>
<thead>
<tr>
<th>Target Source</th>
<th>Target Value (µg/L)</th>
<th>Time Frame</th>
<th>Spatial Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative algal growth rate average $K_a$</td>
<td>28</td>
<td>Summer annual average</td>
<td>Central body of reservoir</td>
</tr>
<tr>
<td>Relative maximum biomass threshold</td>
<td>16</td>
<td>Instantaneous grab</td>
<td>Entire reservoir</td>
</tr>
<tr>
<td>Mean relationship from 1977-1978</td>
<td>8</td>
<td>Annual summer average</td>
<td>Entire reservoir</td>
</tr>
<tr>
<td>Mean relationship for all data</td>
<td>14</td>
<td>Annual summer average</td>
<td>Entire reservoir</td>
</tr>
<tr>
<td>TNRCC CHLA screening level and Figure 7</td>
<td>13</td>
<td>Annual summer average</td>
<td>Central body of reservoir</td>
</tr>
<tr>
<td>Mean relationship from 1977-1978</td>
<td>6</td>
<td>Annual summer average</td>
<td>Dam sites in reservoir</td>
</tr>
<tr>
<td>TNRCC CHLA screening level and Figure 7</td>
<td>14</td>
<td>Annual summer average</td>
<td>Dam sites in reservoir</td>
</tr>
<tr>
<td>Final Technical Workgroup recommendation</td>
<td>10</td>
<td>Annual summer average</td>
<td>Central body of reservoir</td>
</tr>
</tbody>
</table>

Figure 7 and 8 present the results of regression analysis of TIAER monitoring data and historical data supplied by Dr. Owen Lind (Lind, 1979). Figure 7 includes all available data for all sampling sites in Lake Waco. The analysis in Figure 8 is limited to data collected from sampling sites located in the lacustrine area of the reservoir near the dam. Both regressions produce significant, predictive relationships between the PO$_4$-P and CHLA. The historical data from 1977 and 1978 anchor both relationships. Mean algal summer biomass for 1977 and 1978 falls below the TNRCC screening level for CHLA in Texas reservoirs (TNRCC, 1998). In contrast, for a majority of the sites sampled in 1997 and 1998 mean CHLA exceeded the TNRCC screening level (Pearson and McFarland, 1999).

These significant, linear relationships provide the basis for establishing numerical nutrient targets. First, the historical data collected by Dr. Lind provide a temporal reference condition against which we can judge future productivity because their collection predates many of the recent changes in agricultural practices and urban growth thought to be responsible for increased phosphorus loading. The overall, grand mean summer CHLA concentration for the 1977 and 1978 data is 11 µg/L. This level of algal biomass is associated with a grand mean
summer PO₄-P concentration of 8µg/L, providing our third potential nutrient target. In contrast to the historical data, the grand summer means from the entire available data set provide a potential target representative of the long-term average condition in the lake during the summer season. Grand mean summer CHLA and PO₄-P values for all sites and years included in this target evaluation are 20µg/L and 14µg/L, respectively, providing the fourth potential PO₄-P target concentration of 14µg/L (Table 3).

**Figure 7** Regression analysis of CHLA with PO₄-P concentrations for all Lake Waco sites. Regression analysis of annual summer average CHLA concentration and annual summer average PO₄-P concentration for all Lake Waco sites. Analysis based on surface grab samples including historic data from Lind (1979) and TIAER monitoring data from 1997 through 1998. PO₄-P outlier from 6 Sept. 1977 removed from analysis. Triangles = 1977 and 1978 values from Lind and squares = 1997 and 1998 values.

Further target comparisons are possible with this regression analysis. For example, a potential nutrient target can be developed based upon the TNRCC CHLA screening level and the associated PO₄-P concentrations. The TNRCC screening level is based on the 85th percentile of all CHLA measurements made in Texas reservoirs. As such, the screening level represents a broad regional standard. Using the approximate screening value of 20µg/L CHLA as the benchmark, the regression equation in Figure 7 yields the fifth potential PO₄-P target concentration of 13µg/L (Table 3).

These first five potential targets depend upon data collected at multiple sites within Lake Waco. These sites have been positioned along a known physical and chemical gradient that spans the riverine to lacustrine areas of the lake (McFarland et al., 2001). The presence of this gradient enhances the range of the analysis presented in Figure 7 but also introduces the potential confounding factor of physical variation between sites in the reservoir. Although these sites exhibited phosphorus limitation in the nutrient bioassays, the physical conditions along this gradient are significantly different from those observed in the main body of the lake (McFarland et al., 2001). Target development for a more lacustrine area of the reservoir, based upon field data collected from sites located near the dam, was analyzed separately using the regression analysis presented in Figure 8.
Figure 8  Regression analysis of CHLA with PO₄-P concentrations for Lake Waco dam sites. Regression analysis of summer annual average CHLA concentration (April-September; 1977-78; 1997-98) and summer annual average PO₄-P concentration for Lake Waco dam sites. Analysis was based on surface grab samples including historic data from Lind (1979) and TIAER routine monitoring data. Sites were taken from Lake Waco Model (Flowers et al., In prep). PO₄-P outlier from 6 Sept. 1977 removed from analysis. Symbols as in Figure 7.

All of these sites fall within the boundaries of segment 8 of the CE-QUAL-W2 model implementation for Lake Waco (Figure 9; Flowers et al., in prep.). All of the sites also fall into a single group with uniform physical and chemical characteristics (McFarland et al. 2001). Qualitatively, the regression analysis results for sites located in segment 8 (Figure 8) are very similar to those for all Lake Waco sites combined (Figure 7). Significant linear relationships exist between algal biomass and PO₄-P in both cases, but the slopes of these relationships differ. The regression for the sites in segment 8 has a steeper slope and lower y intercept than the relationship for all of the sites. Despite these differences, the potential targets based upon this more restricted analysis are very similar to targets developed from the comprehensive analysis of all sampling sites in Lake Waco. Using the relationship in Figure 8, the potential PO₄-P target based on historical field data dropped from 8µg/L to 6µg/L in this analysis, providing the sixth potential target. In contrast, the seventh suggested PO₄-P target based on the TNRCC screening level has increased from 13µg/L to 14µg/L.

Table 3 summarizes the potential targets presented in the text, providing an overview of the temporal and spatial characteristics of each alternative. The overall range of targets from 8 to 28µg/L PO₄-P span averaging periods of from a few months to a few years. The strongest relationship with the most relevance to the goal of target development appears to be the annual summer average targets derived from Figure 7 and 8.

Technical Work Group Target Recommendations For Lake Waco

The potential PO₄-P nutrient targets were presented to the project Technical Work Group (TWG) convened for the purpose of reviewing and approving both the methods and results of this phase of target development in the Lake Waco-Bosque River watershed. The composition of the workgroup, including affiliations, is presented in Appendix B, "Bosque River-Lake Waco Watershed Technical Work Group." Workgroup members received detailed presentations and interim work products during target development. Final deliberations by the members focused on the alternatives presented in Table 3. After careful consideration, a
Chapter 2  Target Development

target range of between 8 and 14µg/L was identified as desirable. A single numeric PO₄-P target of 10µg/L was also identified to facilitate comparisons between the target and the outcome of analytical modeling and load allocation exercises. All of these targets were generated after lengthy discussions of the scientific merits of the analyses as well as the level of effort to gather the appropriate data. In the end, the targets represented a consensus of the TWG members.

Figure 9  Lake Waco segmentation map from CE-QUAL-W2 model.

North Bosque River Restoration Targets

The approach to developing potential nutrient targets for the North Bosque River followed the same overall approach as that applied to Lake Waco. Algal growth potential bioassays (AGP; USEPA, 1978; APHA, 1995) were performed on water collected at downstream sites on the major tributaries to Lake Waco: South Bosque River (SB060), Middle Bosque River (MB070), Hog Creek (HC065), and North Bosque River (BO100; Figure 10). Monthly bioassays were run using *Selenastrum capricornutum* Printz. as inoculum over a two-year period. The standard algal bioassays were conducted at the limnology laboratory at Baylor University in Waco (see Dávalos-Lind and Lind, 1999).
In addition to these AGP bioassays, a series of in situ stream bioassays were performed to determine the pattern of nutrient limitation. These same bioassays were then used to develop a predictive relationship between nutrient supply and algal production and growth. In-stream bioassays were performed using a recently developed periphytometer technique that supplies specific nutrient treatments to an artificial substrate (Matlock et al., 1998, 1999). Matlock periphytometers are capable of estimating stream trophic status using the ratio of control production to nutrient saturated production. This ratio is referred to as the Lotic Ecosystem Trophic Status Index (LETSI). A similar ratio was used in the Lake Waco target development in Figure 6.

The Matlock periphytometer bioassay is based on substrate colonization and growth in response to nutrient availability. The method integrates water column influences on substrate-specific processes through the use of artificial substrates. Suspended algae capable of a periphytic growth habitat colonize the artificial substrates. Growth-rates on the artificial substrate are regulated by the availability of the limiting nutrient as supplied by the periphytometer, and corresponding rates of biomass accumulation provide estimates of primary productivity. Recent tests have confirmed a correlation between biomass accumulation on the glass fiber filters and primary productivity measured using radiometric...
methods (Rodriguez and Matlock, personal communication). In these bioassays, individual glass-fiber filters were supplied with nitrogen (N), phosphorus (P), or N and P in combination and deployed in the stream in a replicated design to test for nutrient limitation in algal biomass production. Control filters were used to assess in-stream baseline production over the deployment period. Growth and production responses to the treatments were estimated from CHLA production on the respective filters.

A total of eight stream sites within the watershed were tested seasonally using this method. The in-stream periphytometers were deployed at five sites along the North Bosque River (BO020, BO040, BO070, BO090, BO100), one site each on the Middle Bosque River (MB060), Hog Creek (HC065), and at a reference site along Neils Creek (NC060). Data collected represents three different time periods at each site (Matlock and Rodriguez, 1999).

AGP Bioassay Results

Phosphorus was the element limiting growth of *S. capricornutum* Printz. for all tributary sites as indicated from the standard algal growth potential (AGP) bioassay evaluations. The addition of nitrogen to the bioassays produced a very limited growth response above that observed in the bioassay controls (Table 4). In contrast, the addition of phosphorus produced large growth responses in *S. capricornutum* Printz. The fraction of trials at each site exhibiting phosphorus-stimulated growth (i.e., significant growth responses to P addition) exceeded 80 percent for all sites tested by the bioassays (Table 5). All sites indicated a strong general trend towards increased growth under phosphorus additions as compared to control treatments. Assuming the bioassay algae are indicative of in-stream algae responses, all major tributaries to Lake Waco are phosphorus limited immediately downstream of sampling locations.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Algal growth potential (AGP) bioassay results for tributaries of Lake Waco. Mean and standard deviation (n=25) of <em>Selenastrum capricornutum</em> Printz. growth response in fluorescence units to phosphorus and nitrogen additions (fluorescence of treatment minus control) for samples collected December 1996 through November 1998 (Dávalos-Lind and Lind, 1999).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Treatment</td>
</tr>
<tr>
<td>HC065</td>
<td>P Addition</td>
</tr>
<tr>
<td></td>
<td>N Addition</td>
</tr>
<tr>
<td>SB060</td>
<td>P Addition</td>
</tr>
<tr>
<td></td>
<td>N Addition</td>
</tr>
<tr>
<td>MB070</td>
<td>P Addition</td>
</tr>
<tr>
<td></td>
<td>N Addition</td>
</tr>
<tr>
<td>BO100</td>
<td>P Addition</td>
</tr>
<tr>
<td></td>
<td>N Addition</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Summary of nutrient limitation for tributaries of Lake Waco. Percent of treatment means showing a significant growth response of <em>Selenastrum capricornutum</em> Printz. to phosphorus and nitrogen additions (fluorescence of treatment minus control) for samples collected between December 1996 and November 1998 (Dávalos-Lind and Lind, 1999).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td><em>Selenastrum capricornutum</em> Printz. Limitation</td>
</tr>
<tr>
<td></td>
<td>P-Limited (percent)</td>
</tr>
<tr>
<td>HC065</td>
<td>90</td>
</tr>
<tr>
<td>SB060</td>
<td>87</td>
</tr>
<tr>
<td>MB070</td>
<td>90</td>
</tr>
<tr>
<td>BO100</td>
<td>84</td>
</tr>
</tbody>
</table>
Periphytometer Results

The periphytometer results were used to compare growth potential between control treatments and nutrient added treatments for a number of sites (Table 6). In summary, trials at the reference site on Neils Creek (NC060) indicated phosphorus as the limiting nutrient. The North Bosque River sites (BO020, BO040, BO070, BO090, BO100) indicated phosphorus limitation more often than nitrogen limitation, although in the nutrient-enriched environment of the upper North Bosque (i.e., BO020 and BO040), the in situ trials indicated that other factors limited algal growth more than either nitrogen or phosphorus. The North Bosque River sites show a downstream trend of increasing frequency of nutrient limitation (Table 6). Downstream sites have a higher frequency of significant limitation as do reference sites, corresponding with a pattern of higher nutrient concentrations in the Upper North Bosque River watershed (above BO070) as a result of higher nutrient loadings (McFarland and Hauck, 1999b).

Table 6 Summary of nutrient limitation results for Matlock periphytometers. Table 6 displays the number of experiments showing significant nutrient limitation results for Matlock periphytometer deployments in tributaries of Lake Waco. Fifty-three percent of the replicated experiments showed some form of nutrient limitation, with the majority being phosphorus limited.

![Table 6](Image)

In-stream Limiting Nutrient

Taken together, the AGP and periphytometer bioassays indicate phosphorus in the form of PO$_4$-P limits algal growth and production of suspended and attached algae throughout the Bosque River drainage. The effects of enrichment are more pronounced along the Upper North Bosque River, while the reference site on Neils Creek exhibits the most consistent pattern of phosphorus limitation. Downstream sites on the North Bosque River also appear to be phosphorus limited with some regularity.
Some contradictions are present between the results of the two bioassays. While AGP bioassays are phosphorus limited for Hog Creek and the Middle Bosque River water, periphytometers at these sites did not respond to experimental additions of PO$_4$-P. Analysis of control growth rates for periphytometers from the Middle Bosque River did indicate a growth rate response to ambient phosphorus levels (see analysis and discussion below). This was not the case for Hog Creek.

Target Development

As was the case with Lake Waco target development, a number of alternative analyses were undertaken to develop target estimates for the Bosque River drainage with an emphasis on the North Bosque River. Four separate general approaches were used to develop a predictive relationship between in-stream phosphorus and CHLA concentrations for target development. The first method evaluated statistical relationships from monitoring data between annual average CHLA versus phosphorus concentrations from routine grab sampling data from sites throughout the Lake Waco Bosque River watershed. The second approach compared TNRCC screening levels for CHLA with the predictive relationships developed with the first method. The third used the Neils Creek reference site to set a benchmark for ecosystem functions from a minimally impacted watershed. The fourth comparison evaluated the relationship of in situ productivity compared to maximum potential productivity. Matlock’s LETSI measure was plotted as a function of contemporaneous in-stream phosphorus concentrations and fit to the Monod population growth model.

Statistical Relationships From Monitoring Data

In evaluating the stream target, PO$_4$-P was again chosen as the independent variable driving algal productivity and growth. Unlike total-P, PO$_4$-P is not confounded with the dependent variable algal biomass (i.e., algae contain significant amounts of organic phosphorus). Secondly, PO$_4$-P has been shown to predict algal population growth rates according to an external-substrate Monod model (Monod, 1950; Kilham, 1978). Third, aquatic ecosystems enriched through cultural eutrophication are known to have elevated, measurable levels of PO$_4$-P, and this is especially true for the Upper North Bosque River (Pearson and McFarland 1999). In contrast, less productive natural systems have ambient PO$_4$-P concentrations that are often hard to measure because of very low concentrations and very high flux rates between PO$_4$-P and other forms of phosphorus (e.g., Dillon and Rigler, 1974). Fourth, PO$_4$-P had greater predictive power than total-P in explaining observed patterns in the distribution of algal biomass in the field. Finally, PO$_4$-P was the largest component of bioavailable phosphorus in the North Bosque River as measured by the Sharpley (1993) method (TIAER unpublished data).

Monitoring data from January 1997 through December 1998 collected at eight main stem sites along the North Bosque River were compared to TNRCC screening levels for CHLA, PO$_4$-P and total-P (Pearson and McFarland, 1999). While 54 percent of CHLA samples exceeded the screening level of 16.5µg/L, only 2 percent of all samples exceeded the PO$_4$-P screening level of 1400µg/L.

Figure 11, 12, and 13 illustrate three separate relationships between annual average ambient CHLA concentrations and annual average PO$_4$-P concentrations for data collected 1993 through 1998. Analysis was restricted to sites where annual average PO$_4$-P concentrations were less than 500µg/L because primary productivity is nutrient-saturated at in-stream PO$_4$-P concentrations between 70-150µg/L (Figure 11). All three of these figures support the
conclusion that portions of the North Bosque River experience concentrations of $\text{PO}_4\text{-P}$ sufficient to saturate algal biomass growth and accumulation. Figure 11 summarizes annual average data from biweekly grab sampling for all stream-monitoring sites in the Lake Waco Bosque watershed. This includes sites from all of the tributaries to Lake Waco, mainstem sites from the North Bosque River as well as sites on tributaries of the North Bosque.

**Figure 11** Annual average algal biomass as a function of grab sample $\text{PO}_4\text{-P}$ concentration. Annual average algal biomass as a function of ambient $\text{PO}_4\text{-P}$ concentrations < 500µg/L for all grab samples from Lake Waco-Bosque River watershed stream sites. Monod model fit to data is significant at p<0.05 level.

![Graph showing annual average algal biomass as a function of grab sample $\text{PO}_4\text{-P}$ concentration.](image)

**Figure 12** In-stream algal biomass as a function of time-weighted $\text{PO}_4\text{-P}$ concentration. Annual average algal biomass as an exponential function of time-weighted $\text{PO}_4\text{-P}$ concentration for all North Bosque River and tributary sites except BO020, BO040 and SB050. Analysis limited to sites with $\text{PO}_4\text{-P}$ concentration < 500µg/L. Relationship is significant at the p<0.05 level.

![Graph showing in-stream algal biomass as a function of time-weighted $\text{PO}_4\text{-P}$ concentration.](image)
Chapter 2  Target Development

Figure 13  In-stream algal biomass as a function of flow-weighted PO$_4$-P concentration.
Annual average algal biomass as an exponential function of flow-weighted PO$_4$-P concentration for all North Bosque River and tributary sites except BO020, BO040, and SB050. Analysis limited to sites with PO$_4$-P concentrations < 500µg/L. Relationship is significant at p<0.05 level.

The annual average CHLA concentration was determined as the simple arithmetic mean of samples collected on a routine monthly basis for all three figures. The annual average PO$_4$-P calculation for Figure 11 was made more complex because of the availability of biweekly grab samples and temporally intense storm water samples that were collected at intervals less than daily. For monitoring sites with stream flow records, mean daily concentrations were estimated by dividing each annual hydrograph into intervals based on the date and time when water quality samples were taken, applying a midpoint rectangular integration method (Stein, 1977) and appropriate aggregation to calculate a daily PO$_4$-P mass, and dividing the mass by corresponding daily stream flow volume to give a concentration. The annual average PO$_4$-P concentration is then determined as the arithmetic average of all the daily concentrations for each site and year. For sites without stream flow data and storm water sampling, the annual PO$_4$-P concentration was determined by first calculating an average monthly concentration from biweekly sampling (either two or three samples per month) and then averaging the mean concentrations for the 12 months of the year.

For Figure 11, a Monod function has been fit to the data. This model was chosen based on the assumption that algal biomass sampled at a fixed point in a continuously flowing system with a constant resource supply will conform to a simple external nutrient growth model. The $K_s$ of approximately 40µg/L PO$_4$-P from the Monod fit to the ambient concentration data in Figure 11 provides the first potential nutrient target for the North Bosque River. Derived from a watershed-wide response curve, this estimate is anchored on one end by reference sites with minimal production and on the other by enriched sites at near maximum productivity. A threshold level is also visible in Figure 11. As annual average PO$_4$-P reaches 50µg/L, a major discontinuity appears in the data set that provides the second potential target. This discontinuity is also well below the asymptote of the graphical relationship between CHLA and PO$_4$-P.

The robustness of the relationship in Figure 11 was explored using two alternative calculations of average in-stream nutrient concentration. In Figure 12, time-weighted data were used to calculate an annual average PO$_4$-P concentration from monthly flow-weighted concentration data. In Figure 13, annual PO$_4$-P concentration was calculated as the ratio of total annual load divided by total annual flow. Annual average CHLA was fit to these two alternative measures.
of PO₄-P concentration using an exponential model (Figure 12 and 13). Both relationships illustrate the dependence of annual average in-stream CHLA levels on in-stream PO₄-P concentrations. These significant predictive relationships illustrate the functional dependence of primary production on the average availability of the limiting nutrient in this system. Algal biomass responds to the limiting nutrient in a predictable manner regardless of how average in-stream concentration is approximated, illustrating the robust nature of the target development methodology employed in this study.

The third source of a potential target comes from analysis of the watershed reference sites. Reference sites represent sustainable ecosystem function under minimal impacts from anthropogenic sources and provide benchmarks against which we can judge the feasibility of proposed targets. They are a source of real life best-case scenarios in the watershed of interest.

The TNRCC Water Quality Monitoring Program has established Neils Creek as an ecoregion reference in the Lake Waco Bosque River watershed. Analysis of fish communities (Jones, 2000), macrobenthic invertebrate communities (Hendon et al., 1998), and in-stream habitat (Hendon et al., 1998) have established Neils Creek as a site free from major water quality problems. Compared to values for sites located along the North Bosque River, values from Neils Creek for mean CHLA and PO₄-P were much lower than those from sites along the North Bosque River (Table 7). In general, the highest concentrations of CHLA and PO₄-P are found in the upper reaches of the North Bosque River with decreasing concentrations from upstream to downstream locations (McFarland and Hauck, 1998a; Pearson and McFarland, 1999). Using Neils Creek as a reference site, and based on data collected from 1996 through 1998, an annual mean CHLA of 4µg/L could be expected at a PO₄-P concentration of 15µg/L as a benchmark within this ecoregion.

**Table 7** Summary of basic statistics for monthly chlorophyll and biweekly PO₄-P samples. Basic statistic from eight monitoring sites along the North Bosque River compared to reference site data on Neils Creek for January 1996 through December 1999

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>Std.</th>
<th>Min.</th>
<th>Max</th>
<th># Obs.</th>
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</thead>
<tbody>
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<td><strong>CHLA (µg/L)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>North Bosque</td>
<td>27</td>
<td>16</td>
<td>34</td>
<td>0.5</td>
<td>290</td>
<td>430</td>
</tr>
<tr>
<td>Neils Creek</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>0.6</td>
<td>15</td>
<td>48</td>
</tr>
<tr>
<td><strong>PO₄-P (µg/L)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Bosque</td>
<td>340</td>
<td>100</td>
<td>610</td>
<td>2</td>
<td>4510</td>
<td>767</td>
</tr>
<tr>
<td>Neils Creek</td>
<td>14</td>
<td>9</td>
<td>14</td>
<td>2</td>
<td>80</td>
<td>86</td>
</tr>
</tbody>
</table>

The fourth approach involves use of the Lotic Ecosystem Trophic Status Index (LETSI) to develop a predictive relationship between the ecosystem function of interest and the potential target variable. 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). 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 PO₄-P concentrations at the time of the periphytometer deployments (Figure 14). Sites BO020, BO040, BO070, BO090, and BO100 represent a gradient of decreasing ambient PO₄-P and CHLA concentrations as water flows downstream, away from major point and nonpoint sources of nutrient loading (McFarland...
and Hauck, 1999a; 1999b). Figure 14 includes LETSI values calculated from bioassay results for all tributary sites and main stem sites from the Lake Waco Bosque River watershed that exhibited phosphorus limitation or that occurred along the North Bosque River nutrient supply gradient.

**Figure 14** Summary of Matlock periphytometer bioassay results. Functional relationship between LETSI bioassay results and in-stream PO$_4$-P concentrations. Mean LETSI responses from individual deployments are plotted as a function of average in-stream PO$_4$-P concentration measured during the deployment. Monod function is significant at the p<0.05 level.

In situ stream production, measured as the ratio of control to nutrient sufficient production, was a significant function of in situ PO$_4$-P concentrations (Figure 14). Bosque River sites showed a decrease of LETSI values as you moved downstream from site BO040 to BO100. Sites BO020 and BO040 were at nutrient saturated production or MPP. Baseline productivity was saturated at PO$_4$-P concentrations above 200µg/L. The reference site NC060 had a LETSI of 0.4 at a PO$_4$-P concentration of 15µg/L. Sites showing little or no P limitation (BO020 and BO040) had LETSI values very close to unity, consistent with the predictions of the method (Matlock et al., 1998). Dose-response PO$_4$-P treatments show reference-site nutrient sufficient growth at 50µg/L. A Monod equation was fit to the data using the Lineweaver-Burk parameter estimation method to calculate the K$_s$ (Lehninger, 1975). LETSI attains 50 percent of its asymptote at a PO$_4$-P concentration of 40µg/L, providing the last potential nutrient target.

**Summary of Potential Stream Targets**

Table 8 summarizes the potential PO$_4$-P target values based upon the various assessment methods. As was the case with Lake Waco, all potential targets are defined in terms of the putative limiting nutrient in the system, PO$_4$-P. Targets were derived from analysis of ambient monitoring data, reference site comparisons, and in situ experimental results. Targets were developed from the relationships discussed above and summarized in Table 8.
Table 8  Potential nutrient restoration targets for North Bosque River.
Potential nutrient targets to be used as restoration criteria and their sources. All targets are in terms of average annual summer values as defined in the text. Values are derived from various approaches described in the text.

<table>
<thead>
<tr>
<th>Target Source</th>
<th>PO₄-P Target Value (µg/L)</th>
<th>Time Frame</th>
<th>Spatial Distribution</th>
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</thead>
<tbody>
<tr>
<td>Kₛ from the Monod fit to the annual average grab sample data</td>
<td>40</td>
<td>Annual average</td>
<td>Entire basin</td>
</tr>
<tr>
<td>Threshold level from the Monod fit to the annual average grad</td>
<td>50</td>
<td>Annual average</td>
<td>Entire basin</td>
</tr>
<tr>
<td>Reference site annual mean</td>
<td>15</td>
<td>Annual average</td>
<td>North Bosque River</td>
</tr>
<tr>
<td>Kₛ from the Monod fit to the dose-response / LETSI data</td>
<td>40</td>
<td>Grab average</td>
<td>North and Middle Bosque Rivers</td>
</tr>
</tbody>
</table>

From these relationships, a summary of potential PO₄-P targets was presented to the Technical Work Group that also reviewed Lake Waco targets. An initial consensus target range of 15 to 50µg/L PO₄-P as an annual average was set for the North Bosque River at Meridian (BO085), Clifton (BO090), and Valley Mills (BO100). This recommendation was reviewed and modified to 30µg/L PO₄-P as an annual average by a subcommittee of the Bosque River Advisory Committee for the Lake Waco-Bosque River watershed. The approved target was forwarded to additional subcommittees of the BRAC for incorporation into a recovery plan for the watershed.
CHAPTER 3

Discussion

The major challenge to achieving watershed-based solutions through integrated basin management is understanding how linkages between terrestrial and aquatic ecosystem components drive water quality. Aquatic and terrestrial components of basins are tightly coupled by nutrient and carbon cycles (e.g., Hynes, 1975). When these natural ecosystem functions are disrupted or overwhelmed by pollutants such as nutrients that originate from point and nonpoint sources, restoring water quality becomes an exercise in re-establishing these cycles. By focusing on watersheds, integrated basin management can design and test selective management actions, which aim to restore specific, degraded ecosystem functions like nutrient cycling and carbon assimilation. Once implemented, individual management actions need to be evaluated for success, and one critical measure of that success is the attainment of specific targets or indicators of ecosystem function. Evaluation for success is especially important for basins degraded by nonpoint source pollution known to originate from land-use conversions and inadequate management practices.

Measurable targets are necessary to monitor the success or failure of best management practices or other nutrient management efforts. By definition, a nutrient management program that meets its target(s) is a programmatic success. If the correct target value was chosen, attainment of the target should also indicate the end of the water quality problem in the basin, which is the more relevant measure of a successful target. In order for this water quality measure to be met, the assessment variable used as the target must either have a cause and effect (i.e., mechanistic) relationship with the water quality impairment or have a well known correlation (i.e., co-linearity) with the water quality problem of concern. If either of these conditions is true, then a change in target variable value will have a high probability of indicating a meaningful change in the water quality of receiving waters.

Our analysis has demonstrated that in-lake and in-stream algal biomass varies as a function of ambient PO₄-P concentrations. Additional tests of this functional relationship for both the Lake Waco and North Bosque River ecosystems have also revealed that algal biomass accumulates according to a predictive, mechanistic model of resource-dependent growth with PO₄-P as the limiting resource. Given the level of documentation presented supporting a cause and effect relationship between phosphorus availability and algal biomass, PO₄-P concentrations are a reasonable indicator of ecosystem function and health for the Lake Waco-Bosque River watershed. Specific targets defined in terms of average PO₄-P concentrations have a high probability of tracking ecosystem response to any future restoration activities in the watershed.

The actual numeric values of the targets presented in Chapter 2, “Target Development”, compare favorably with the literature values discussed in Chapter 1, “Introduction”. The Lake Waco consensus target of 10µg/L is identical to past suggestions from Vollenweider (1968) and Sawyer (1947). The 30µg/L target for the North Bosque River is also well within the range of the published in-stream limits reviewed in Chapter 1, “Introduction”.

The targets developed here are directly related to the water quality problems identified by previous studies. Each target is based on a mechanistic link between the limiting nutrient and
algal growth and production. This link is the basis of a predictive relationship between the target (P) and the measure of impairment subject to control during implementation (CHLA). However, these relationships are limited by two factors: the short duration of the study (two years) and the use of in-lake and in-stream spatial gradients to predict future water body responses to changes in loading and runoff. Because of these limitations, targets for Lake Waco and the North Bosque River should continue to be reviewed and refined on a regular basis.

The proposed targets have already been used in the evaluation of proposed best-management practices (BMPs) within the Lake Waco-Bosque River watershed. Watershed-loading (SWAT) and reservoir simulation (CE-QUAL-W2) modeling have been applied to evaluate the effectiveness of BMPs in meeting the proposed targets. As part of this process, the management practices available have been modeled to determine the feasibility of meeting these proposed targets through nonpoint and point source load allocation/reduction in the Lake Waco-Bosque River watershed. The results of these modeling studies will help guide the development and implementation of watershed restoration plans based in large part on the targets developed in this report. The success of specific management actions will be judged by future water quality conditions in the component water bodies. Nutrient targets or other numeric benchmarks must be a part of the measurement of this success if the process is to be credible.


Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, PR9904 (August 1998).


Bosque River-Lake Waco Sampling Sites

Sites on the North Bosque River

Sampling on the North Bosque River was conducted at eight sites, beginning upstream at BO020 above Stephenville and continuing downstream to BO100 near Valley Mills. Routine grab samples were collected at all eight sites on the North Bosque River, while storm event samples were taken at sites BO020, BO040, BO070, BO090 and BO100.

The land uses above the North Bosque River sites do not vary greatly from site to site. Of note, however, is a general decrease in percentage of permanent pasture and dairy waste application fields and a general increase in percentage of land designated as woodland, range and cropland from upstream sites to downstream sites.

Six cities are located along the North Bosque River. These cities, listed upstream to downstream, are Stephenville (16,000), Hico (1,500), Iredell (370), Meridian (1,500), Clifton (3,600) and Valley Mills (1,200).

North Bosque River above Stephenville (site BO020): Site BO020 is located on the North Bosque River, at the crossing of State Highway 8 on the northeast boundary of Stephenville. BO020, an automated sampler site, is located just below the confluence of the North and South Forks of the North Bosque River. The drainage area for BO020 is primarily rural but does contain a small portion of the city of Stephenville.

North Bosque River below Stephenville Wastewater Treatment Plant (site BO040): Automated sampler site BO040, located on the North Bosque River approximately one quarter mile below the Stephenville wastewater treatment plant (WWTP), is the only North Bosque River site located directly below a municipal WWTP discharge. The site is located at the crossing of CR 454; about five miles below site BO020. Although the WWTP is a dominant influence on the water quality at BO040 during low flow conditions, the drainage area includes storm water runoff from the city of Stephenville and from many of the rural land areas above and around Stephenville.

North Bosque River near Green Creek (site BO060): Site BO060, a grab sampling site, is located on the North Bosque River about 14 miles downstream of site BO040 at the crossing of CR 248. Tributaries entering the river between site BO060 and BO040 include Indian and Sims Creeks.

North Bosque River at Hico, Texas (site BO070): Automated sampler site BO070 is located near U.S. Geological Survey (USGS) station 08094800 on the North Bosque River at the crossing of U.S. Highway 281 in Hico, Texas. The drainage area of this site is referred to as the upper North Bosque River watershed in most TIAER data analysis reports. BO070 is located about seven river miles downstream of site BO060 and about one mile above the WWTP discharge for the city of Hico.
North Bosque River at Iredell (site BO080): Site BO080 is located on the North Bosque River below the confluence of Duffau Creek with the North Bosque River. Monitoring is limited to biweekly physical measurements and grab sample analysis. BO080 is located about 14 river miles downstream of site BO070 and above the city of Iredell WWTP discharge.

North Bosque River at Meridian (site BO085): This monitoring site is located on FM Road 2840, west of Meridian. Monitoring is limited to biweekly physical measurements and grab sample analysis. BO085 is located about 17 river miles downstream of site BO080 and above the city of Meridian WWTP discharge.

North Bosque River at Clifton (site BO090): Automated sampler site BO090 is located near USGS station 08095000 on the North Bosque River near the crossing of FM Road 219, about half a mile northeast of Clifton, Texas. BO090 is located approximately 14 river miles downstream of BO085 and above the city of Clifton WWTP discharge.

North Bosque River at Valley Mills (site BO100): Automated sampler site BO100 is located south of the USGS station 08095200 on the North Bosque River near the crossing of FM Road 56 northeast of Valley Mills. BO100 is located about 12 river miles downstream of BO090 and about 28 river miles upstream from the mouth of the North Bosque River at Lake Waco. The discharge for the Valley Mills WWTP is located below site BO100.

Sites on Major Tributaries to Lake Waco

The North, Middle and South Bosque Rivers, and Hog Creek represent the major tributaries to Lake Waco. Each tributary is monitored using automatic storm samplers and routine manual grab samples. BO100 is included both in this category and in the North Bosque River category because it is the nearest North Bosque River site to Lake Waco.

The land uses within the watersheds of these four tributaries vary considerably. Range and woodland dominate the North Bosque River watershed, with considerable dairy activity, while the South and Middle Bosque and Hog Creek watersheds contain more cropland. Site BO100, on the North Bosque River, is the only one of the four sites on major tributaries to Lake Waco having substantial dairy activity within its drainage area. One dairy is located in the Middle Bosque River watershed, but it is located downstream of the MB060 sampling site. About three percent of the drainage area above BO100 is designated as dairy waste application fields, almost all of which occurs in the upper portion of the North Bosque River watershed above site BO070 (McFarland and Hauck, 1998). The drainage area above BO100 contains over 746,000 acres, while the drainage areas above sites HC060, MB060, SB050 and SB060 each contain less than 77,000 acres.

North Bosque River at Valley Mills (site BO100).

Hog Creek (site HC060): An automated sampler is located on Hog Creek at the crossing of FM Road 185 near USGS station 08095400 about 6 miles east of Crawford, Texas. Site HC060 is about 10 miles upstream from Lake Waco. The majority of the land area above the Hog Creek site is characterized as either cropland or range, with no influence from dairy operations.

Middle Bosque River (sites MB060 and MB070): An automated sampler is located on the Middle Bosque River MB060 site, located east of Crawford at the crossing of FM Road 185, approximately 12 miles upstream from Lake Waco. The city of Crawford (700) is located below site MB060. Site MB070 is located approximately 1.5 miles north of US Highway 84 on Speegleville cutoff near the McGregor Municipal Airport. The land area above the Middle
Bosque site is dominated by cropland, with the remaining land characterized primarily as wood and range.

South Bosque River (sites SB050 and SB060): Site SB060 is located on the South Bosque River at FM Road 2837, south of US Highway 84. Site SB050 is located on private property on Church Road, about \(\frac{3}{4}\) miles south of US Highway 84. The automatic sampler installed in January 1997 was moved upstream to site SB050 in July 1997 due to backwater impacts from Lake Waco. The location of the site SB050, however, presented safety hazards for personnel trying to obtain grab samples. Therefore, grab samples representing the South Bosque River are taken at site SB060, while storm samples are taken at Site SB050. The city of McGregor (4,800) is located within the South Bosque River watershed, about 10 miles above sampling sites SB050 and SB060. The land area above the South Bosque sites is dominated by cropland, with no influence from dairy operations. Because of their proximity and the complementary nature of the sampling regimes, the data from the two sites are combined for this report.

**Sites on Lake Waco**

Lake Waco covers about 7,270 acres and a longitudinal distance of 14 miles in McLennan County (TNRCC, 1996). The City of Waco originally constructed Lake Waco in 1929 as a municipal water supply. The lake was enlarged in 1964 by the U.S. Army Corps of Engineers for flood control, conservation storage, and recreation. Lake Waco is formed by a rolled earthfill dam. As part of the TIAER Lake Waco sampling program, grab samples are generally collected 1 foot below the surface, 1 foot above the bottom of the lake and at a mid-depth between the surface and bottom depth. Hydrolab readings are also generally taken at 1-meter (3.28 feet) intervals for DO, pH and conductivity to profile the lake's water quality characteristics with depth.

Lake Waco N. Bosque Arm (site LW010): LW010 is located in the upper reservoir arm near the North Bosque River midchannel upstream from FM 185 Bridge.

Lake Waco mouth of N. Bosque (site LW011): LW011 is located at the mouth of the North Bosque River. The site is marked by a buoy at the confluence of the river with the reservoir.

Lake Waco N. Bosque Arm (site LW012): LW012 is at midchannel at the lower end of the original North Bosque River channel. The site is midchannel between Reynolds Creek and Airport Park.

Lake Waco at structure of dam (site LW013): LW013 is located at the structure of the dam approximately 30 yards to the southwest of the structure.

Lake Waco Middle & South Bosque arm (site LW015): LW015 is located between the State Highway 6 bridge and a buoy to the north of the bridge approximately midchannel.

Lake Waco near mouth of Hog creek (site LW016): LW016 is located at the white buoy near the south shore just inside the mouth of Hog Creek.

Lake Waco at S. Bosque arm (site LW017): LW017 is located near the mouth of the South Bosque River on the north side of the channel.

Lake Waco at Langdon Branch arm (site LW020): LW020 is located at the center buoy that marks the confluence of Langdon Branch with the reservoir. Langdon Branch enters the reservoir at the dam.
Lake Waco at body of lake (site LW030): LW030 is located in the body of the reservoir just south of the dam.

Lake Waco between dam and retainer gates (site LW040): LW040 is located at a point between the dam and the retainer gates.

Lake Waco at body of lake (site LW050): LW050 is located in the body of the reservoir southwest of the spillway at the north end of the dam.

Lake Waco between bridge and dam (site LW060): LW060 is located approximately midway between the State Highway 6 bridge and the dam. The site is midchannel between the boat launch off Overflow Road and the boat launch on Lake Shore Drive (south shore).

Lake Waco at Speegleville I Park (LW070): LW070 is located at a white buoy directly in front of the Bosque Bend Clubhouse at Speegleville I park on the west shore of the lake.
Bosque River-Lake Waco Watershed Technical Work Group

(Participants during nutrient target discussions)

<table>
<thead>
<tr>
<th>Agency</th>
<th>Representatives</th>
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<tbody>
<tr>
<td>Texas Natural Resource Conservation Commission</td>
<td>Clyde Bohmfalk (Chair)</td>
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<td></td>
<td>Jim Davenport</td>
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