Assessment of Water Quality Trends for the North Bosque River Through 2022

Jimmy Millican and Todd Adams

North Bosque River Station 17226 (BO020) above Stephenville, TX (April 3, 2023)

Prepared July 2023 for the Texas Commission on Environmental Quality,
Office of Water, Water Quality Planning Division

TR2307

TCEQ AS-216/22

Published October 2023

Assessment of Water Quality Trends for the North Bosque River Through 2022

Report to
Total Maximum Daily Load Program
Office of Water, Water Quality Planning Division,
Planning and Implementation Section
Texas Commission on Environmental Quality
Austin, Texas

Contract No. 582-20-13159 Work Order No. 11

Prepared by
Jimmy Millican and Todd Adams
Texas Institute for Applied Environmental Research
Tarleton State University
Stephenville, Texas

Millican, J. and T. Adams. 2023. Assessment of Water Quality Trends for the North Bosque River Through 2022. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR2206 and Austin: Texas Commission on Environmental Quality, AS-216/22.

TR2307
TCEQ AS-216/22
October 2023

Acknowledgements

The Texas Commission on Environmental Quality (TCEQ) Total Maximum Daily Load Program (Contract No. 582-20-13159 Work Order No. 11) provided financial support for preparation of this report. The report has been produced annually with financial support from the Total Maximum Daily Load Program since 2018.

The Texas Institute for Applied Environmental Research (TIAER) collected and analyzed all historical water quality monitoring data presented herein. Past support includes Clean Water Act (CWA) Section 319(h) projects *Evaluating Effectiveness of Total Maximum Daily Load Implementation Plan Activities within the North Bosque River Watershed, North Bosque River Watershed Water Quality Assessment,* and *Evaluating Effectiveness of Implementation Plan Activities within the North Bosque River Watershed* funded through the TCEQ Nonpoint Source Program by the U.S. Environmental Protection Agency. Other major projects that supported historical monitoring include *Livestock and the Environment: A National Pilot Project* sponsored by EPA, the *Bosque River Watershed Pilot Project* funded through the TCEQ Clean Rivers Program in cooperation with the Brazos River Authority, and the *Lake Waco-Bosque River Initiative*, funded through the U.S. Department of Agriculture.

TIAER initially developed the historical information regarding spatial distribution of animal waste application fields in the watershed under the 2006 TCEQ project, *Monitoring to Support North Bosque River Model Refinement*, with the Total Maximum Daily Load Program. Updates to these spatial data occurred under the Clean Water Act Section 319(h) project, *Evaluating Effectiveness of Implementation Plan Activities within the North Bosque River Watershed*, and this current project.

The U.S. Geological Survey provided flow and rating curve information for three gauging stations they maintain along the North Bosque River.

The authors would also like to acknowledge the dedicated work of the many field personnel and laboratory chemists who aided in the collection and analysis of samples, particularly since nonpoint source water quality monitoring often requires personnel to be on-call seven days a week.

Mention of trade names or commercial products does not constitute their endorsement.

Table of Contents

List of Tables

List of Figures

Introduction

This report presents an update of water quality trends in the North Bosque River watershed, assessing effectiveness of nonpoint source (NPS) and point source control measures associated with the North Bosque River Total Maximum Daily Loads (TMDLs) Implementation Plan (I-Plan). This report largely follows the format of previous trend reports for the North Bosque River (e.g., McFarland and Millican, 2011 and 2012; McFarland and Adams, 2013, 2014a, 2015, 2016, 2017, and 2018; Millican, Adams, and McFarland 2019; and Millican and Adams, 2020, 2021, and 2022). Trend analyses focus on seven monitoring stations, five of which are index stations (17226 [BO020], 11963 [BO040], 18003 [BO083], 11956 [BO090], and 11954 [BO095]),[1] for the phosphorus TMDLs along the North Bosque River (Figure 1). Other stations include station 11961 (BO070), a long-term monitoring station located along the North Bosque River between index stations 11963 (BO040) and 18003 (BO083), and station 13486 (GC100), located on a major tributary to the North Bosque River. Spatial information on concentrated animal feeding operations (CAFOs), animal feeding operations (AFOs), and the land area associated with waste application fields[2] (WAFs) is also updated within this report to aid in evaluating implementation practices within the watershed.

TCEQ adopted two TMDLs for soluble reactive phosphorus[3] (SRP) for North Bosque River Segments 1226 and 1255 in February 2001, which U.S. Environmental Protection Agency (EPA) approved in December 2001 (TNRCC, 2001). Jointly, these two segments represent the full length of the North Bosque River from its headwaters just north of Stephenville, where the North Fork and South Fork of the Upper North Bosque River merge, to its confluence with Lake Waco in McLennan County. The goal of these TMDLs is an overall reduction of about 50% in SRP loadings and concentrations within the North Bosque River, with specific reduction goals varying by the river reach. The I-Plan for these TMDLs was approved by TCEQ in late 2002 and by the Texas State Soil and Water Conservation Board (TSSWCB) in early 2003 (TCEQ and TSSWCB, 2002).

The I-Plan outlines a number of programs to reduce SRP in the North Bosque River. These programs include four basic elements for phosphorus control:

---

[1] Throughout this report, stations are identified with both the TCEQ station identification number and the TIAER identification to allow easy referencing to earlier reports where only one or the other may have been used to identify stream sampling locations.

[2] WAFs are land areas where animal waste is applied as organic fertilizer and are considered separately from pasture and cropland areas that receive solely commercial fertilizer. Most WAFs are associated with CAFOs and AFOs, as noted in McFarland and Jones (2006) and Houser and Hauck (2010).

[3] Soluble reactive phosphorus is the form directly taken up by plant cells and is commonly measured as orthophosphate phosphorus (PO_4-P).

1. Use of phosphorus application rates for land application of dairy manure,
2. Use of reduced phosphorus diets for dairy cows to decrease manure phosphorus,
3. Removal of about half the dairy-generated manure from the watershed, and
4. Implementation of phosphorus effluent limits at municipal wastewater treatment facilities (WWTFs).

To address phosphorus application rates on dairy WAFs, TSSWCB initiated the Comprehensive Nutrient Management Plan (CNMP) Program. TSSWCB supports the voluntary implementation of CNMPs by dairy producers as part of their water quality management plans (WQMPs) for AFOs. In addition to voluntary compliance, TCEQ amended rules[4] for CAFOs in 2004 to require regulated dairies in the North Bosque River watershed to implement nutrient management plans (NMPs). On July 2, 2014, TCEQ adopted a revised CAFO rule to incorporate changes to federal regulations. These rule changes imposed additional requirements regarding NMPs for CAFOs in the watershed.

An NMP addresses nutrient management guidance for cropping systems as part of a conservation plan for producers and landowners. A CNMP encompasses most aspects of an NMP, but additionally may include specifications for feed management, manure and wastewater handling and storage, nutrient management, land treatment practices, and other manure and wastewater utilization options addressing the overall agronomic and environmental aspects of an animal feeding operation (TCEQ and TSSWCB, 2002). The development and adoption of CNMPs and NMPs has occurred over several years. In state fiscal year (FY) 2006, eight CNMPs were certified; 34 were certified in FY2007, and another seven were certified in FY2008 (TCEQ, 2009). In FY2009, TSSWCB indicated that two more CNMPs were certified. By the end of 2010, all 55 dairy CAFOs that were operating in the watershed in 2004 had certified CNMPs, adding substantive nutrient management practices to their operations (TCEQ, 2012a). TSSWCB continues to review and certify, as appropriate, new or amended plans.

Anecdotal evidence from dairy producers supported by local feed specialists and Texas AgriLife Extension Service (formerly Texas Cooperative Extension) indicates that producers are implementing lower phosphorus diets. In the mid to late 1990s, a survey of dairy diet formulations including dairies in the North Bosque River watershed indicated that cow diets averaged 0.52% phosphorus (Sansinena et al., 1999). Revised recommendations by the National Research Council (NRC) indicate optimal levels of about 0.38 percent phosphorus for high-producing dairy cattle (NRC, 2001), which has been supported in studies focused on reducing excess phosphorus in manure (e.g., Powell and Satter, 2005; Miller et al., 2010; Kebreab, et al., 2013).

---

[4] Subchapter B Concentrated Animal Feeding Operations, Chapter 321, Texas Administrative Code Title 30, Section 321.31 and Section 321.40.

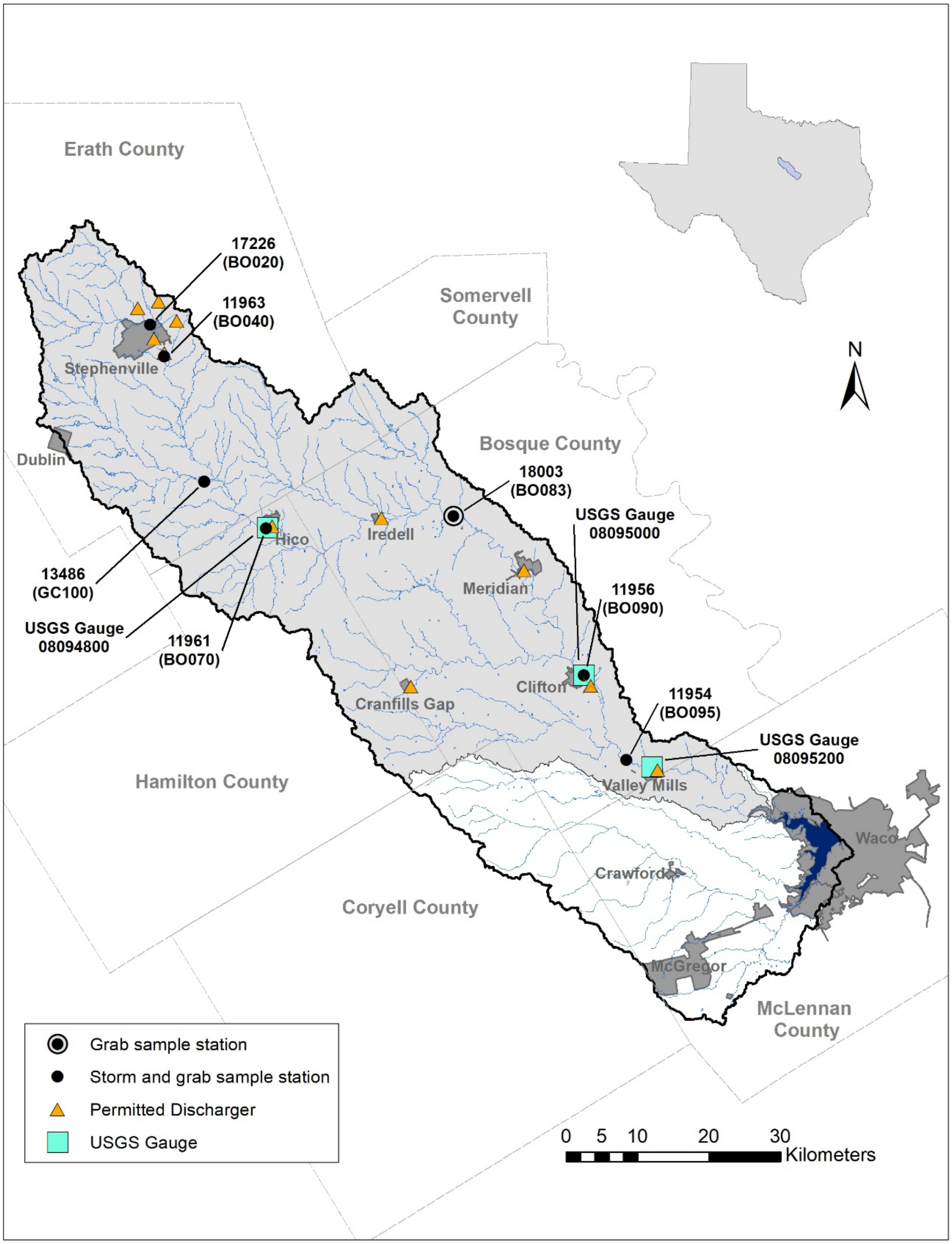

Figure 1 North Bosque River watershed trend analysis monitoring stations and USGS gage locations

Sample station identifier – TCEQ (TIAER).

In dealing with the export of manure from the watershed, the two most visible projects associated with the I-Plan were the Dairy Manure Export Support (DMES) project and the Composted Manure Incentive Project (CMIP). TSSWCB sponsored the DMES project to provide incentives to haulers to transport manure from dairies to composting facilities. Through the CMIP, TCEQ provided oversight of composting facilities and rebates to Texas state agencies that used manure compost associated with the DMES project. TCEQ and TSSWCB initiated these manure composting projects in September 2000 to export roughly 50% of the dairy manure in the watershed at that time out of watershed, while providing a beneficial soil amendment. The Texas Department of Transportation (TxDOT) was the major user of dairy manure compost for roadside revegetation. Through August 2006, over 650,000 tons of dairy manure were hauled to composting facilities and about 329,000 cubic yards of compost were exported from the watershed (TCEQ, 2009).

Funding for the CMIP continued through August 2006, while the DMES project continued to pay incentives to haulers through February 2007. The idea behind these two projects was to establish a manure composting industry that would be self-sufficient after these two incentive programs ended. Seven composting facilities were active during these projects. As of 2022, there are only two active commercial composting facilities, Erath Earth and Green Cow Compost, both located in Dublin, Texas, just on the western edge of the watershed. There are also dairy operations within the watershed that compost their own manure, but that number is not readily available. CAFOs in the North Bosque watershed are currently required under their permits to either export manure outside the watershed, send it to an approved composting facility, or apply it to either their own or third-party WAFs within the watershed at specific rates. Soil must be tested for phosphorus levels at a WAF annually and before the first-time waste is applied; waste cannot be applied if phosphorus levels in soil exceed certain criteria.

Another measure that has had a notable impact on water quality, particularly under low-flow conditions, is the implementation of phosphorus-removal treatments by municipal WWTFs. There are seven municipal WWTFs that discharge within the North Bosque River watershed—Stephenville, Hico, Meridian, Iredell, Cranfills Gap, Clifton, and Valley Mills. As part of Phase I in the I-Plan, initial waste load allocations (WLAs) were set for all seven municipal WWTFs and phosphorus reporting was implemented. The permits for the two largest facilities, in Clifton and Stephenville, were amended in 2003 to require phosphorus limits that necessitate advanced treatment processes. In the fall of 2005, Stephenville began using biological treatment in conjunction with alum and polymers for phosphorus removal, with the goal of meeting a daily average discharge limit of one milligram per liter (1 mg/L). The Clifton WWTF started using alum as a chemical treatment to remove phosphorus in the spring of 2005.

As Phase II of the WWTF measures, permits for existing municipal permittees and other wastewater dischargers were amended to require phosphorus load limits in pounds per day and/or a one milligram per liter (1 mg/L) total-phosphorus (total-P) effluent concentration limit. As of Aug. 31, 2010, TCEQ reported that all seven municipal WWTFs within the North Bosque River watershed had compliance schedules consistent with the WLAs in the TMDLs and I-Plan (TCEQ, 2011). There are also two other nonmunicipal dischargers within the watershed that have phosphorus limits (Table 1 and Figure 1).

With implementation of all these activities, it is important to monitor and statistically evaluate improvements in water quality. Changes in water quality may be gradual and usually lag actual implementation on the land, particularly with regard to reducing nonpoint source pollutants (e.g., Meals, et al., 2010). There has also been temporal and spatial variability in the implementation of I-Plan activities, so it may take several more years after implementation occurs before instream improvements become apparent throughout the watershed.

Direct point source discharges occur to the North Bosque River from each community's WWTF, with the exception of Cranfills Gap and Hico (Table 1). The Cranfills Gap WWTF discharges into the Austin Branch of Meridian Creek, a major tributary to the North Bosque River, and the Hico WWTF discharges into Jacks Hollow Branch a few hundred feet before its confluence with the North Bosque River. Two additional wastewater dischargers are as follows:

- Northside Subdivision WWTF for the Northside Subdivision Water Plant and Distribution Corporation located about 0.75 miles east of North State Highway (Hwy) 108 and 0.75 miles south of County Road 433, north of Stephenville.

- The Shady Oaks WWTF owned by the Stephenville Mobile Home Park located at the intersection of US Hwy 377 and Business US Hwy 377 northeast of Stephenville.

To evaluate improvements in water quality, TIAER has sampled stream stations all along the North Bosque River since late 1995. Prior to 1995, TIAER's monitoring focused on stream stations and tributaries within the upper third of the watershed, providing a sampling history at some stations dating back to 1991. While SRP is the focus of the North Bosque River TMDLs, excessive nutrients, based on a variety of nitrogen and phosphorus constituents, elevated chlorophyll-α (CHLA) concentrations, and elevated bacteria levels have been a concern in the North Bosque River watershed for quite some time. To better determine improvements in the North Bosque River, trends are presented for nitrogen, phosphorus, CHLA, total suspended solids (TSS), specific conductance (conductivity), and bacteria concentrations. Field parameters (e.g., dissolved oxygen and pH), while routinely monitored as instantaneous measurements, were not included in this trend analysis due to the difficulty in correcting for diurnal fluctuations. Besides trends analysis, data were also evaluated in comparison to attainment of water quality goals specified in the TMDL I-Plan, and results are discussed in the context of I-Plan activities.

Table 1 Phosphorus WLA for wastewater discharges within the North Bosque River watershed

Permitted Discharge	Permit ID TCEQ (EPA)	Latitude	Longitude	Total Phosphorus Daily Avg. (mg/L)	Total Phosphorus Daily Avg. (lbs/day)[a]	Permitted Monthly Discharge (MGD)[a]	Discharge Location
City of Stephenville	WQ0010290001 (TX0024228)	32.197850	-98.18762	1	29.2[b]	3.5[b]	North Bosque River
City of Clifton	WQ0010043001 (TX0033936)	31.785277	-97.568333	Report	7.0	0.65	North Bosque River
City of Meridian	WQ0010113002 (TX0053678)	31.920139	-97.65444	Report	5.9	0.45	North Bosque River
City of Valley Mills	WQ0010307001 (TX0075647)	31.663333	-97.463611	Report	3.0[c]	0.36	North Bosque River
City of Hico	WQ0010188001 (TX0026590)	31.978333	-98.026944	1	2.1	0.25	Jacks Hollow Branch of the North Bosque River
City of Iredell (Town Plant WWTF)	WQ0011565001 (TX0024848)	31.987103	-97.86455	Report	1.7	0.049	North Bosque River
City of Cranfills Gap	WQ0014169001 (TX0122360)	31.773655	-97.823223	Report	0.4	0.04	Austin Branch, thence to Meridian Creek, and thence to the North Bosque River
Northside Subdivision Water Corporation	WQ0014735001 (TX0128996)	32.254444	-98.221944	Report	0.28	0.033	Unnamed tributary of the North Fork North Bosque River, thence to the Upper North Bosque River
Stephenville Mobile Home Park (Shady Oaks WWTF)	WQ0013966001 (TX0132039)	32.238353	-98.164966	Report	0.20	0.024	Unnamed tributary, thence to Pole Hollow Branch; thence to the Upper North Bosque River
Western Dairy Transport	WQ0004314000 (Not Applicable)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	No discharge

a. MGD = million gallons per day; lbs/day = pounds per day. Source for MGD values: Permit files obtained online through TCEQ Central Registry Query ().

b. Total phosphorus and permitted discharge include both outfalls for Stephenville. Outfall 001 discharges below Stephenville, while outfall 002 discharges within the Stephenville City Park inside the city.

c. Source: North Bosque River I-Plan (TCEQ and TSSWCB, 2002). Also, noted in permit for the City of Valley Mills under Other Requirements.

Background and Station Descriptions

North Bosque River Watershed

The North Bosque River is located in central Texas and extends about 110 river miles from Stephenville, Texas to Lake Waco near Waco, Texas (Figure 1). The headwaters of the North Bosque River originate in Erath County just north of Stephenville. Lake Waco, a man-made reservoir, supplies drinking water to over 150,000 people. The North Bosque River watershed comprises about 74% of the land area draining into Lake Waco. Other major tributaries to Lake Waco include Hog Creek, Middle Bosque River, and South Bosque River. The urban population in the North Bosque River watershed has increased about 32% over the past 25 years, with Stephenville, the watershed's largest city, encompassing most of this growth (Table 2).

The North Bosque River watershed is typical of many watersheds in the region in that the dominant land covers are woodland and range. Improved pasture and some row crop farming occur throughout the watershed. Row crop farming is most common in the southern portions of the watershed, particularly in the floodplain of the North Bosque River close to the city of Clifton. Improved pasture is predominately fields of Coastal Bermuda grass (*Cynodon dactylon*), while row crops of sorghum (*Sorghum bicolor*) and winter wheat (*Triticum* spp.) are often grown as a double-crop system. Most dairies are located within the upper third of the watershed, where producers have traditionally applied dairy waste as organic fertilizer to improved pasture and row crops.

Table 2 Estimated populations and growth for municipalities within the North Bosque River watershed

Municipality	Estimated 1990 Population[a]	Estimated 2000 Population[a]	Estimated 2010 Population[b]	Estimated 2020 Population[b]
Stephenville	13,502	14,921	17,123	21,194
Hico	1,342	1,341	1,379	1,422
Iredell	339	360	339	345
Meridian	1,390	1,491	1,493	1,526
Cranfills Gap	269	335	281	286
Clifton	3,195	3,542	3,442	3,609
Valley Mills	1,085	1,123	1,203	1,252

a. Population estimates are based on values presented by the Texas State Data Center based on U.S. Census data for 1990 and 2000 (Texas State Data Center, 2015).

b. Revised 2010 Census Count and estimated 2020 population (Texas Demographic Center, 2020).

Erath County, where the river originates, was consistently the number one milk-producing county in Texas between 1990 and 2010. Since 2011, Erath County has remained one of the top six milk-producing counties. The number of dairy producers in Erath County peaked in 1994 and since has decreased markedly (Figure 2). Milk production peaked in 2000 and has also decreased, but the decrease has not been proportional to the decline in producers. Though milk production has decreased overall, there was a notable resurgence in milk production between 2014 and 2022. Part of this increase can be related to increased milk production per cow. Throughout the United States, milk production has increased about 10% per cow over the last 10 years according to U.S. Department of Agriculture-National Agricultural Statistics Service statistics (USDA-NASS, 2023). Between 2014 and 2022 in Erath County, milk production has increased over 39%, indicating an increase in cow numbers as well. While Erath County expands beyond the range of the North Bosque watershed, about two-thirds of the dairy operations in Erath County are located within the North Bosque River watershed, so county-level statistics likely reflect dairy production within the watershed. Based on TCEQ inspection records for the North Bosque River watershed, the estimated number of dairy cows was about 45,000 in 2001 and about 43,000 in 2022[5].

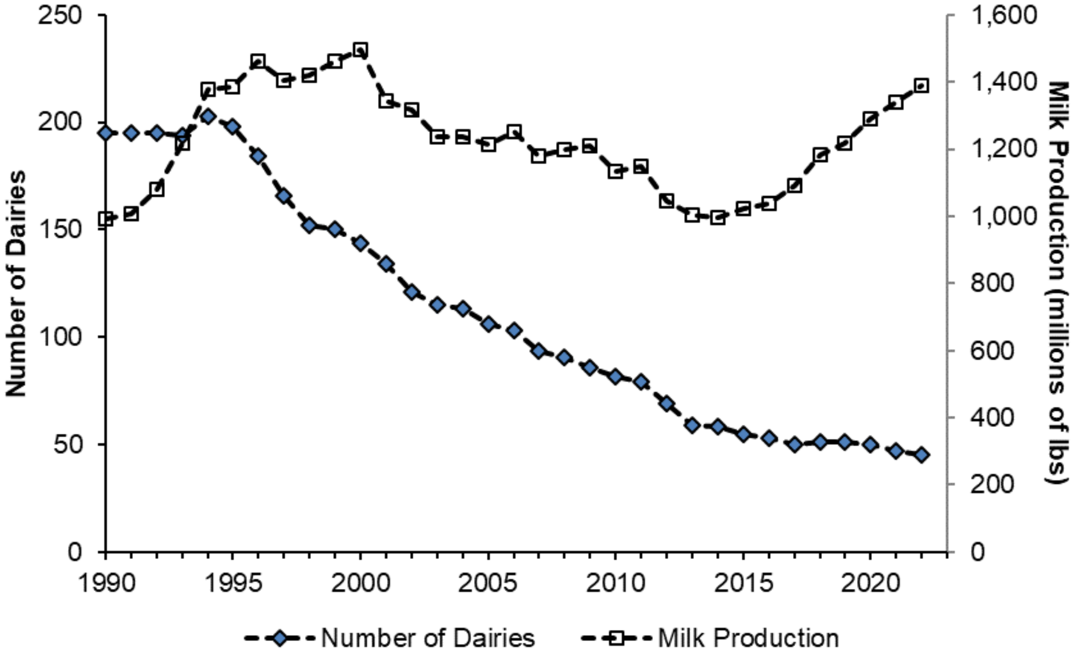

Figure 2 Annual variation in the number of dairy producers and milk production for Erath County

Source: United States Department of Agriculture, Agricultural Marketing Service milk marketing production records.

Annual rainfall in the North Bosque River watershed averages 32.4 inches per year. Rainfall typically follows a slightly bimodal pattern, with peaks in the spring and fall (Figure 3). On average, the wettest month is May, and the driest month is January. Most tributaries of the North Bosque River are highly intermittent and frequently become dry soon after each rainfall-runoff event. In some years, winter rains corresponding with low evapotranspiration rates can establish a base flow that persists well into spring. Groundwater contributions in the upper portion of the watershed are generally insignificant, though groundwater seepage has been noted in the lower portion of the watershed.

---

[5] Because TCEQ no longer annually inspects all CAFOs within the watershed, estimated animal numbers for 2022 are based on inspected values from FY2010 through FY2022, using the most recent inspected value for active operations as the estimate for FY2022.

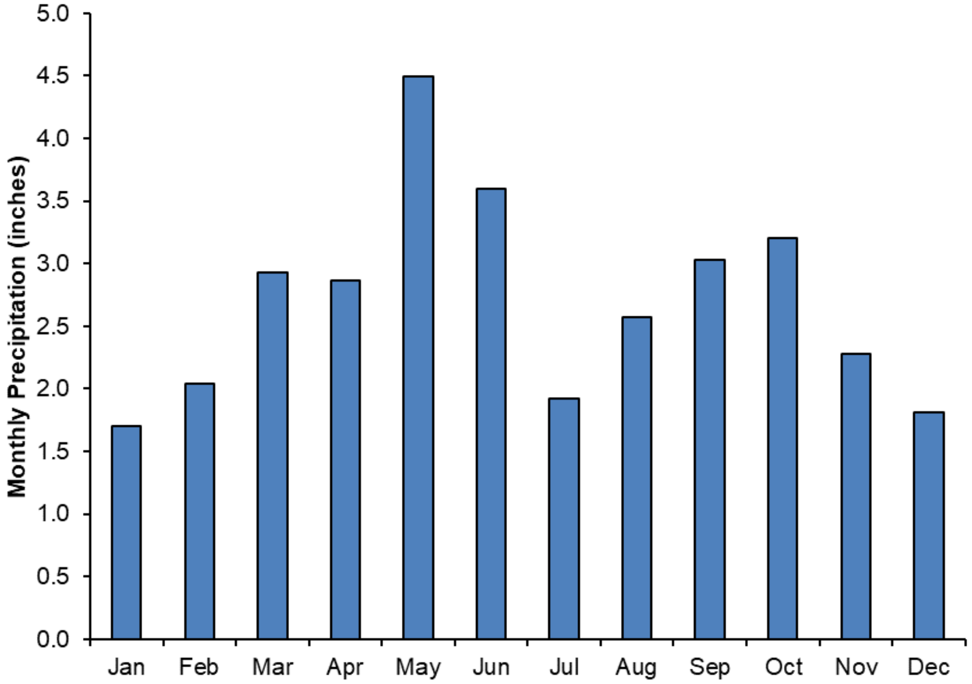

Figure 3 Average monthly normal precipitation for Stephenville, Texas (1993-2022)

Source: National Oceanic and Atmospheric Administration, National Climatic Data Center.

Sampling Stations

Because TIAER has sampled at many of these stations under separate projects, all stations are listed by both their TCEQ and TIAER station identifications for easy reference to information or data in other reports. The TCEQ station identification number is generally listed first, followed by the TIAER station identification in parentheses or brackets. Trend analyses focused on seven stream stations at which temporally intensive data collection has occurred for several years. Monitoring at most stations was initiated in the early to mid-1990s, though monitoring at station 18003 (BO083) was not initiated until 2003. These stations vary in drainage area, water quality, and hydrology (Table 3) and are grouped as follows:

- The five North Bosque River index stations (11954 [BO095], 11956 [BO090], 18003 [BO083], 11963 [BO040], and 17226 [BO020]) specified in the phosphorus TMDLs and I-Plan.
- North Bosque River at Hico, station 11961 (BO070), which is in a long reach of the river between index stations.
- Green Creek, station 13486 (GC100), which has been collocated with one of TCEQ's Environmental Monitoring and Response System (EMRS) stations and gathers data from a subwatershed that is primarily influenced by nonpoint sources of phosphorus.

General land-use descriptions are based on the National Land Cover Database (NLCD) 2016 (USGS, 2019), supplemented with information summarized by TIAER on animal waste application fields within the watershed (Table 3). A notable decrease in the percentage of urban land-use cover as compared to percentages previously reported is due to a refinement in the 2016 NLCD layer that improved the accuracy in identifying roads. The Spatial Sciences Laboratory of the Texas Agricultural Experiment Station, now Texas AgriLife Research, conducted a land-use classification for the watershed based on satellite imagery from 2001 through 2003 (Narasimhan et al., 2005; Table 3).

Information on animal waste application fields was compiled in 2000 from TCEQ records, modified in 2005, and updated again in the fall of 2007 by TIAER, based on a review of TCEQ permit information used to supplement this satellite imagery classification (McFarland and Jones, 2006; Houser and Hauck, 2010). The WAF information included milking and nonmilking operations, with milking operations representing over 80% of the CAFOs and AFOs in the watershed. TIAER updated WAF information through 2022 related to CAFOs and AFOs in the watershed for the purposes of this report to aid in evaluating if changes in the amount and location of WAFs might be related to changes in water quality.

In addition to the stations listed in Table 3, data from station 17605 (BO100) were used in conjunction with data from station 11954 (BO095) for trends analysis. Station 17605 (BO100) was a TIAER sampling station located northeast of Valley Mills that was discontinued in July 2001 due to bank stability problems. Station 11954 (BO095) was installed as a replacement site about 1.9 river miles upstream of station 17605 (B0100). The discharge for the Valley Mills WWTF is located below station 17605 (BO100). Data from these two stations will be collectively referred to as station 11954 (BO095) throughout the rest of this report.

Table 3 Estimated land use and drainage area above sampling sites

Station Identification TCEQ (TIAER)	Location within the North Bosque River Watershed	Drainage Area (hectares)	Dominant Land Use or Land Cover[a]	General Water Quality and Hydrology
17226 (BO020)	North Bosque River above Stephenville, Texas	21,700	Woodland-range (34%), pasture and cropland (41%), WAFs (19%), urban (6%)	Water quality moderately impacted by nonpoint sources; intermittent flow with perennial pools
11963 (BO040)	North Bosque River below Stephenville, Texas, about 0.6 km below the discharge from the Stephenville WWTF	25,700	Woodland-range (32%), pasture and cropland (41%), WAFs (17%), urban (9%)	Water quality impacted by point and nonpoint sources; perennial flow
11961 (BO070)	North Bosque River at Hico, Texas, above the discharge from the Hico WWTF	93,100	Woodland-range (38%), pasture and cropland (45%), WAFs (10%), urban (6%)	Water quality moderately impacted by point and nonpoint sources; nearly perennial flow
18003 (BO083)	North Bosque River between Iredell and Meridian, Texas	178,000	Woodland-range (57%), pasture and cropland (28%), WAFs (8%), urban (5%)	Water quality moderately impacted by point and nonpoint sources; nearly perennial flow
11956 (BO090)	North Bosque River at Clifton, Texas, above the discharge from the Clifton WWTF	253,000	Woodland-range (57%), pasture and cropland (31%), WAFs (5%), urban (6%)	Low impacts from point and nonpoint sources; perennial flow
11954 (BO095)	North Bosque River at Valley Mills, Texas above the discharge from the Valley Mills WWTF	297,000	Woodland-range (59%), pasture and cropland (32%), WAFs (5%), urban (4%)	Low impacts from point and nonpoint sources; perennial flow
13486 (GC100)	Green Creek near the confluence with the North Bosque River	25,200	Woodland-range (38%), pasture and cropland (48%), WAFs (9%), urban (5%)	Water quality moderately impacted by nonpoint sources; intermittent flow with perennial pools

a. WAFs are land areas where animal waste is applied as organic fertilizer and are considered separately from pasture and cropland areas that receive solely commercial fertilizer. Most WAFs are associated with CAFOs and AFOs, as noted in McFarland and Jones (2006) and Houser and Hauck (2010).

Sample Collection and Laboratory Analysis Methods

Quality Assurance Procedures

Beginning as early as 1992, TIAER collected data from project stations under a variety of quality assurance project plans (QAPPs). Historical information used in this report includes water quality, rainfall, and streamflow data. Historical project QAPPs include the following:

- QAPP for the National Pilot Project (TIAER, 1993) funded by EPA. This QAPP covers data collected between June 1, 1992 and Aug. 31, 1995 for stations in the upper portion of the North Bosque River watershed.

- QAPP for the Bosque River Watershed Pilot Project (BRA, 1995) funded by the TCEQ Clean Rivers Program via the Brazos River Authority, with TIAER as a subcontractor. This QAPP covers data collected between Oct. 1, 1995 and May 31, 1996.

- QAPP for the Lake Waco-Bosque River Initiative (TIAER, 2005) funded by the U.S. Department of Agriculture. This QAPP covers data collected between Sept. 1, 1996 and Aug. 31, 2006.

- QAPP for the North Bosque River Watershed Water Quality Assessment Clean Water Act Section 319(h) project funded by TCEQ and EPA Region 6 (TIAER, 2010a). This QAPP covers data collected between February 2006 and August 2010.

- QAPP for the North Bosque River Watershed Water Quality Assessment project funded through the TCEQ Surface Water Quality Monitoring Program (TIAER, 2010b). This QAPP covers data collected between September 2010 and August 2011.

- QAPP for Evaluating Effectiveness of I-Plan Activities within the North Bosque River Watershed, a Clean Water Act Section 319(h) project funded through the TCEQ NPS Program (TIAER, 2013, amended in July 2015 to extend monitoring through August 2016). This QAPP covers data presented in this report collected between September 2011 and August 2016.

- QAPP for Evaluating Effectiveness of Total Maximum Daily Load (TMDL) Implementation Plan (I-Plan) Activities within the North Bosque River Watershed, a Clean Water Act Section 319(h) project funded through the TCEQ NPS Program (TIAER, 2016). This QAPP covers data presented in this report collected between September 2016 and August 2017.

- QAPP for Evaluating Effectiveness of TMDL I-Plan Activities within the North Bosque River Watershed, funded through the TCEQ TMDL Program (TIAER, 2017, revised 2023). This QAPP is for the current project and covers data collected between September 2017 and May 2024.

Water quality data associated with the projects above were collected and analyzed using similar assessment objectives, sampling techniques, laboratory protocols, and data validation procedures. The sampling design was changed in the spring of 2008 due to a decrease in funding. Prior to 2008, an effort was made to sample all storms, but after 2008, only selected storms were monitored. This change has continued for storm monitoring through 2022. Information regarding storm monitoring is outlined by year from 2008 through 2021 in Appendix A and for 2022 under the section "Collection Methods for Storm Samples."

A second known area of deviation has been in the collection of routine grab samples during pooled or no streamflow conditions. Prior to September 2021 routine grab samples were only collected if streamflow was present. Beginning in September 2021, TIAER began collecting samples regardless of streamflow conditions at stations 17226 (BO020) and 13486 (GC100). Collection of routine grab samples regardless of streamflow conditions began occurring at all other stations in September 2022.

A third known area of deviation has been in the measurement of bacteria over time. Prior to 2000, fecal coliform (FC) rather than *Escherichia coli (E. coli)* was monitored. McFarland and Millican (2010) evaluated paired *E. coli* and FC data from November 2000 through March 2004 to compare these two types of bacteria data. This period of overlap was used to determine if FC could be adjusted to comparable *E. coli* values using accepted statistical methods for comparing different analytical methods (Bland and Altman, 1986). This comparison included 1,075 paired observations and produced the following regression relationship, which was used to adjust historical fecal coliform concentrations to *E. coli* concentrations prior to trend analysis.

$$\ln(E.\ coli) = 0.946*\ln(\mathrm{FC}) - 0.029 \qquad R^2 = 0.93 \qquad p = <0.0001$$

Of note, McFarland and Millican (2010) indicate that this regression relationship did not meet all the assumptions associated with use of regression analysis in that the distribution of residuals was peaked, and thus, not normally distributed even after data were log normally transformed. McFarland and Millican assumed that the regression relationship between fecal coliform and *E. coli* was robust enough that the violation of this statistical assumption would have only a minor impact on the outcome of the trend analysis.

A fourth known deviation was in the use of reporting limits for left-censored data. Prior to September 2003, TIAER used laboratory method detection limits (MDLs) as reporting limits for constituents. After September 2003, TIAER used TCEQ ambient water reporting limits (AWRLs) or limits of quantitation (LOQs) as reporting limits. Data for each constituent were standardized prior to trend analysis to make sure that differences in the reporting limit did not cause an indication of false trends, as described later in this report under the section on data set construction.

Data external to TIAER from the U.S. Geological Survey (USGS) were used to determine flow at some sampling stations. The USGS maintains stage gaging stations along the North Bosque River near Hico (USGS station 08094800), Clifton (USGS station 08095000), and Valley Mills (USGS station 08095200). Associated USGS stream stage, discharge, and/or rating curve data were used in conjunction with data collected by TIAER to calculate discharge at stations 11961 (BO070), 11956 (BO090), and 11954 (BO095).

The overall objective of monitoring water quality in the watershed since 2011 has been to use data collected specifically for evaluation of the North Bosque River TMDL I-Plan in conjunction with historical data from previous projects to evaluate changes in water quality over time. Because most historical data were collected and analyzed in a comparable manner, no limitations were placed on their use, except where known deviations occurred, such as the changes in bacteria parameters and differences in reporting limits mentioned previously.

Collection Methods for Routine Grab Samples

Routine grab sampling at stream stations occurred at least monthly and generally on a biweekly schedule through August 2021. Beginning in September 2021, stations 17226 (BO020) and 13486 (GC100) were sampled on a biweekly schedule and the other five stations were sampled on a monthly schedule. Through August 2021, grab samples were collected only when water was flowing at a station and not when the stream was dry or pooled. Beginning September 2021, sampling occurred at stations 17226 (BO020) and 13486 (GC100) regardless of flow conditions if a sufficient pool was present. Beginning September 2022, the sampling frequency was reduced to monthly at stations 17226 (BO020) and 13486 (GC100) and to every other month at the remaining five stations. Also beginning in September 2022 all stations were sampled regardless of streamflow conditions if a sufficient pool was present.

Grab samples were collected in all years at a depth of 0.3 m or less below the surface depending on total water depth, as indicated in TCEQ surface water monitoring procedures (TCEQ, 2003; 2008; 2012b). When grab samples were collected, water temperature, dissolved oxygen (DO), pH, and conductivity were measured in situ with a Hydrolab or YSI (multiprobe) field-sampling instrument. Because stream stations within the North Bosque River watershed are generally shallow and the water column unlikely to stratify at these locations, multiprobe readings were taken only at a surface depth corresponding to the depth of the routine grab sample. Flow measurements were also collected (or estimated if flow was too high or too low for direct measurements) at most sites. When necessary, flow estimates were derived by using data from a nearby USGS gauging station, stream level data from automated sampling locations and associated rating curves, or float test estimation. Due to access issues, flow data generally could not be collected for station 18003 (BO083).

In this report, surface samples are presented and evaluated for trends in nutrients, TSS, CHLA, bacteria (as *E. coli*), and conductivity. Trends in water temperature, DO, and pH were not evaluated, because many physical parameters, particularly water temperature and DO, follow a diurnal pattern that causes values to vary depending on the time of day when measurements are taken.

Collection Methods for Storm Samples

Storm samples were collected at six of the seven North Bosque River stream sampling stations. Only routine grab samples were collected at station 18003 (BO083) due to issues with accessibility for installation of a storm sampling station, which also hindered direct measurement of flow at this location.

The collection of storm samples at automated sampling stations used an ISCO 3700 sampler in combination with an ISCO 4230 or 3230 bubbler-type flow meter. The ISCO flow meter operates by measuring the pressure required to force an air bubble through a 3-millimeter (mm) (0.125 in) polypropylene tube, or bubbler line, and represents the water level. The ISCO flow meters were programmed to record water level or stage continuously at five-minute intervals and to initiate sample retrieval by the ISCO 3700 samplers. Samplers typically were actuated based on a stream rise of about 4 cm (1.5 in) above the bubbler datum. Once activated, samplers were programmed to retrieve one-liter sequential samples. Historically, the typical sampling sequence at major tributary and mainstem stream stations was:

- An initial sample
- One sample taken at a one-hour interval
- One sample taken at a two-hour interval
- One sample taken at a three-hour interval
- One sample taken at a four-hour interval
- One sample taken at a six-hour interval
- All remaining samples taken at eight-hour intervals

Since the fall of 2006, the sampling sequence has been modified so that once the four-hour interval was encountered, all remaining bottles for an event were then taken at four-hour intervals. If an automated sampler could not activate or became inoperable during a storm event, daily storm grabs were generally collected to represent the event.

Until June 1997, most sequential storm samples within an event collected by an automated sampler were analyzed individually by TIAER's laboratory. To decrease sample load to the laboratory, a flow-weighting strategy was initiated that composited samples on about a daily basis. This flow-weighting strategy was initiated at stations 17226 (BO020), 11963 (BO040), 11961 (BO070), and 13486 (GC100) in May or June 1997 and at stations 11956 (BO090) and 11954 (BO095) in May 2000.

At each storm sampling station, stream stage was continuously monitored at five-minute intervals (or 15-minute intervals, if USGS stage or flow recordings were used). To convert stage readings to flow, stage-discharge relationships were developed. For stations 17226 (BO020), 11963 (BO040), and 13486 (GC100), stage-discharge relationships were based on manual flow measurements by TIAER staff taken at various stage conditions that were then related to the cross-sectional area of the stream, following USGS methods as outlined in Buchanan and Somers (1969). Stage-discharge relationships for stages without available discharge measurements were extrapolated using the cross-sectional area and a least-squares relationship of the average stream velocity to the log of water level or expansion of a fitted polynomial regression line.

Stations 11961 (BO070), 11956 (BO090), and 11954 (BO095) are located near USGS stream gauging stations (Figure 1). Station 11961 (BO070) is located near USGS station 08094800, 11956 (BO090) is located near USGS station 08095000, and 11954 (BO095) is located near USGS station 08095200. Very early in TIAER's monitoring program, stage recordings at station 11961 (BO070) were tied into the USGS rating curve for station 08094800. The daily average discharge values at station 08094800 were used as a check on the TIAER estimates of discharge at station 11961 (BO070) until October 1999, when the USGS station 08094800 near Hico was converted to a flood-hydrograph partial record station. In mid-January 2016, USGS reinitiated reporting all flows for station 08094800 near Hico. TIAER relied primarily on stage and flow data measured at station 11961 (BO070) from 2016 through 2022 but has used flow and stage data at USGS station 08094800 to aid in filling in gaps.

For flows at station 11956 (BO090), instantaneous USGS data from station 08095000 are used in this report. For station 11954 (BO095), instantaneous USGS data from station 08095200 are used. In October 2005, the USGS station 08095200 near Valley Mills was converted to a flood-hydrograph partial record station. To obtain continuous discharge measurements after Oct. 1, 2005, a period with USGS discharge measurements and TIAER stage recordings was used to develop a stage-discharge relationship for station 11954 (BO095) in conjunction with manual flow measurements collected by TIAER. This new rating curve for station 11954 (BO095) was used for discharge estimates after Oct. 1, 2005, and USGS 15-minute discharge data were used prior to Oct. 1, 2005. Starting in September 2007, the USGS station near Valley Mills (08095200) was converted back to recording all flows. Since 2007, TIAER has relied primarily on instantaneous flow data from the USGS station 08095200 for flows at station 11954 (BO095).

Monitoring Conditions

Within Appendix A, general monitoring conditions between 2008 and 2020 are presented. Following is a summary of conditions in 2022 outlining storms monitored.

2022

Throughout 2022 the North Bosque River watershed experienced drought conditions that were classified as moderate drought conditions in January 2022 to severe and extreme drought conditions for the remaining months of 2022. This resulted in historically low streamflow conditions and a lack of opportunity to collect a sufficient amount of storm samples.

In 2022, storms were monitored during April, May and October. Three storms were monitored at station 11963 (BO040). Two storms were monitored at stations 17226 (BO020), 11961 (BO070), and 11956 (BO090). One storm was monitored at station 11954 (BO095). No storms were monitored at station 13486 (GC100) as it remained pooled throughout the year.

Precipitation in Stephenville within the headwaters of the North Bosque River totaled 22.1 inches for 2022, considerably below the long-term average of 32.4 inches. Drought conditions persisted in the North Bosque River watershed area throughout 2022.

Laboratory Analysis Methods

Ammonia-nitrogen (NH_3-N), nitrite-nitrogen plus nitrate-nitrogen (NO_2-N+NO_3-N), total Kjeldahl nitrogen (TKN), orthophosphate-phosphorus (PO_4-P) or SRP, total-phosphorus (total-P), and TSS were evaluated for both routine grab and storm samples (Table 4). In addition, CHLA and *E. coli* were evaluated for routine grab samples. Total nitrogen (total-N) was derived as the sum of NO_2-N+NO_3-N plus TKN.

Prior to 2000, fecal coliform rather than *E. coli* was monitored as an indicator of bacteria concentrations. From November 2000 through March 2004, both fecal coliform and *E. coli* were analyzed to determine a relationship between these two measures of bacteria.

Table 4 Parameters and methods of analysis for water quality samples used in trend analysis

Parameter	**Abbreviation**	**Units**	**Method**[a]	**Parameter Code**
Ammonia-nitrogen	NH_3-N	mg/L	EPA 350.1 or SM 4500-NH3 G	00608
Nitrite-nitrogen + nitrate-nitrogen	NO_2-N+NO_3-N	mg/L	EPA 353.2 or SM 4500-NO3-F	00631
Total Kjeldahl nitrogen	TKN	mg/L	EPA 351.2 or SM 4500-NH3G[b]	00625
Orthophosphate-phosphorus	PO_4-P	mg/L	EPA 365.2 or SM 4500P-E	70507 or 00671[c]
Total phosphorus	Total-P	mg/L	EPA 365.4[b]	00665
Total suspended solids	TSS	mg/L	EPA 160.2 or SM 2540 D	00530
Chlorophyll-α	CHLA	µg/L	SM10200-H	32211
Escherichia coli	*E. coli*	cfu/100 mL or MPN/100mL	IDEXX Colilert®[d]	31699

a. EPA refers to *Methods for Chemical Analysis of Water and Wastes* (USEPA, 1983) and SM refers *to Standard Methods for the Examination of Water and Wastewater, 18th Edition* (APHA, 1992) for PO_4-P and latest online edition for all other parameters.

b. TKN and total-P methods modified to use copper sulfate as the catalyst instead of mercuric oxide.

c. Field-filtering for PO_4-P began in October 2003 for routine grab samples (code 00671). All routine samples prior to October 2003 and all storm samples were lab filtered (code 70507).

d. Most probable number (MPN) or IDEXX method for E. coli was implemented in April 2004.

Data Set Construction and Statistical Methods for Trend Analysis

Two data sets representing monthly estimates of average constituent concentrations for each station were developed for trend analysis. The first data set came from routine grab data, while the second data set combined routine grab and storm data. Trends associated with these two data sets address TMDL objectives regarding reductions in concentrations and loadings. Routine grab samples should reflect any decrease in concentrations associated with routine monitoring, while the volume-weighted data set including storm samples should reflect any decreases in stream loadings.

Most routine grab samples for nutrients and TSS were collected biweekly, while samples for analysis of CHLA and bacteria were usually collected only monthly. So, in the first data set, measurements or estimates of instantaneous discharge were paired with each biweekly or monthly grab sample as an indicator of flow conditions. Because variation in sampling frequency over time can cause unintended impacts on the analysis of trends (Gilbert, 1987), concentrations and flows were averaged monthly. Except at station 18003 (BO083), which did not have flow data. Concentrations for trend analysis represented monthly flow-weighted averages to account for differences in instantaneous flow between individual grab samples within a month. At station 13486 (GC100), insufficient samples occurred in 2011 (only one), 2013 (only one), and in 2014 (none) for evaluating trends of routine grabs for these end years. Trends for station 13486 (GC100) were updated in this report for data through 2022, noting these gaps.

The second data set represented volume-weighted, average-monthly constituent concentrations based on calculations of total flow and loadings using routine grab and storm samples. Monthly masses and flows were calculated using a rectangular integration method applying a midpoint rule to associate water quality concentrations with streamflow (Stein, 1977). The interval for stage readings (generally five minutes for TIAER stations and 15 minutes for USGS gauging stations) was the minimum measurement interval. The flow associated with each interval was multiplied by the associated average monthly water quality concentration and summed across the entire month to calculate total monthly constituent loadings. Monthly volume-weighted concentrations were calculated by dividing total monthly mass for a constituent by total monthly volume of flow.

As noted earlier for routine grab samples, trends of loading data were not analyzed for station 13486 (GC100) in 2011, 2013, and 2014 due to a lack of monitoring data associated largely with dry weather conditions, although bridge work also made this station inaccessible during much of 2014. Trends through 2022 were evaluated for station 13486 (GC100), as the method used is robust enough to handle these missing data.

Censored Data

Analytical laboratories generally present data based on a reporting limit, where the reporting limit is the lowest concentration at which the laboratory quantitatively reports data values as different from zero. Values below the reporting limit are generally indicated as less than the reporting limit or left-censored. Left-censored data can cause problems with trend analysis, especially when changes in the reporting limit occur over time. If differences due to variation in reporting limits are not accounted for prior to trend analysis, false trends may be observed. For example, if a relatively high reporting limit is used early and a lower reporting limit later in a project, a decreasing trend may be statistically shown that would not exist if concentrations from the earlier data were actually lower than the later reporting limit. As part of the quality assurance of a project, reporting limits should be low enough that relevant changes in values can be observed.

For most projects prior to September 2003, TIAER used laboratory MDLs as the reporting limit. These MDLs were updated about once every six months. After September 2003, most TIAER projects used TCEQ-defined AWRLs or LOQs as the reporting limit, although if not specified for a project, MDLs were still implemented. Following recommendations by Gilliom and Helsel (1986) and Ward et al.

(1988), values measured below the laboratory reporting limit or left-censored data were entered as one-half the reporting limit. Since variations in reporting limits have occurred, the highest minimum reporting limit was determined for each constituent. In preparing data sets for trend analysis, the highest minimum reporting limit for each station by constituent was set equal to one-half the maximum reporting limit.

Monitoring History

Because monitoring was conducted under several different projects, different lengths of record were available for each station that varied some by parameter (Tables 5 and 6). Stations 11961 (BO070) and 13486 (GC100) had the longest periods of record, with data starting in 1993. With routine grab samples, TKN, total-P, and TSS were not analyzed until 1994 at 11961 (BO070) and 1995 at 13486 (GC100), but these three constituents were analyzed with storm samples starting in 1993. Loading estimates at 11961 (BO070) in 1993 and 13486 (GC100) in 1993 and 1994 for TKN, total-P, and TSS were, thus, based on only storm data. Also, at 13486 (GC100), CHLA was not a routine parameter until 1996. Consistent data sets for all constituents were indicated at station 17226 (BO020) starting in 1997; at station 11963 (BO040) as of 1994; and at stations 11956 (BO090) and 11954 (BO095) of 1996.

Exploratory Data Analysis

Exploratory data analysis (EDA) was used to initially evaluate each data set. The EDA graphical technique is used to characterize distributional properties, identify outliers and patterns, and select appropriate statistical tests using primarily histograms and box plots (Tukey, 1977). Histograms and the Shapiro-Wilk statistic were used to test for normality. The Shapiro-Wilk statistic showed that most water quality variables were not normally distributed. Natural log ($\log_e$ abbreviated as ln) transformation improved the distribution and homogeneity of variance for routine grab and volume-weighted data sets.

Table 5 Years of available sampling data for trend analysis by station and parameter type for routine grab samples

Station	**Conductivity**	**Soluble Nutrients**	**TKN, Total-P, and TSS**	**CHLA**	**Bacteria**
17226 (BO020)	1997 – 2022	1997 – 2022	1997 – 2022	1997 – 2022	1997 – 2022
11963 (BO040)	1994 – 2022	1994 – 2022	1994 – 2022	1994 – 2022	1994 – 2022
11961 (BO070)	1993 – 2022	1993 – 2022	1994 – 2022	1993 – 2022	1994 – 2022
18003 (BO083)	2003 – 2022	2003 – 2022	2003 – 2022	2003 – 2022	2003 – 2022
11956 (BO090)	1996 – 2022	1996 – 2022	1996 – 2022	1996 – 2022	1996 – 2022
11954 (BO095)	1996 – 2022	1996 – 2022	1996 – 2022	1996 – 2022	1996 – 2022
13486 (GC100)[a]	1993 – 2022	1993 – 2022	1995 – 2022	1996 – 2022	1995 – 2022

Sample data for station 13486 (GC100) were extremely limited in 2011, 2013, and 2014.

Table 6 Years of available sampling data for trend analysis by station and parameter type for storm samples

Station	Soluble Nutrients	TKN, Total-P, and TSS
17226 (BO020)	1997 – 2022	1997 – 2022
11963 (BO040)	1994 – 2022	1994 – 2022
11961 (BO070)	1993 – 2022	1993 – 2022
18003 (BO083)	not applicable	not applicable
11956 (BO090)	1996 – 2022	1996 – 2022
11954 (BO095)	1996 – 2022	1996 – 2022
13486 (GC100)[a]	1993 – 2022	1993 – 2022

Sample data for station 13486 (GC100) were extremely limited in 2011, 2013, and 2014.

Time series and box-and-whisker plots identify patterns and describe variability in the data. In addition, time series and box plots provide insight regarding the presence of trends and seasonality. Seasonality is a systematic variation that, if present, confounds the true trend. Removing seasonality prior to trend analysis is important because a significant positive trend in one season and a significant negative trend in another season can result in a finding of no trend when evaluated together. The presence of seasonality was statistically evaluated using correlograms of monthly data as described by Reckhow et al. (1993). A correlogram expresses how the correlation of pairs of water quality data changes with time. A significant correlation at lags representing 6 and 12 months generally indicates seasonality (Reckhow et al., 1993). A significant correlation at shorter lags (lags representing one or two months) indicates autocorrelation. For the parameters and sites evaluated, seasonality was not significant.

Adjustment for Stream Flow

Another confounding factor in trend analysis of stream water quality data is variation in flow or volume and its influence on concentration. For example, at stream stations where point source contributions dominate, increased flows associated with storm runoff may act to dilute concentrations, so concentrations decrease with increasing flows. In contrast, at stream stations where NPS contributions dominate, increasing concentrations may occur with increasing flow. Details on methods for removing ancillary effects associated with flow are discussed in Helsel and Hirsch (2002). The two most commonly used methods are simple linear regression and locally weighted scatterplot smoothing (LOWESS) (Helsel and Hirsch, 2002; Cleveland, 1979). The LOWESS method is preferred over simple linear regression as an adjustment method because the relationship between most ancillary variables, such as flow or volume and concentration, is usually nonlinear (Helsel and Hirsch, 2002; Bekele and McFarland, 2004).

The LOWESS method is an extension of simple linear regression, in that it fits simple regression models to localized subsets of the data to build up a function that describes the deterministic variation between two variables. The local regression is fit using weighted least squares, giving more weight to points near the point whose response is being estimated and less weight to points further away. A user-specified input called the "smoothing parameter" (*f*) determines how much data are used to fit each localized regression. Values off range from zero to one, with one using each individual data point as in simple linear regression. Large *f* values produce the smoothest functions that "wiggle" the least in response to fluctuations in the data, while smaller *f* values fit functions that more closely conform to the data. Using too small an *f* value is not desirable, because the regression function will start to capture random error in the data (SAS Institute, 2011).

An *f* value of 0.5 was used as recommended by USGS (Langland et al., 1998) and later confirmed to be optimum for data from the North Bosque River watershed (Bekele and McFarland, 2004). The PROC LOESS procedure of SAS (SAS Institute, 2011) was used to develop the LOWESS regression relationships. Residuals associated with the LOWESS regression of flow with concentration were then used in trend testing as flow-adjusted concentrations. At stream stations, monthly average stream flow was calculated as the average of instantaneous measures with grab samples or as the total volume of flow divided by the number of seconds in a month with volume-weighted data. Flows and concentrations were transformed using a natural-log transformation prior to applying the LOWESS regression to decrease the variance in the regression residuals.

Trend Testing

The presence of a trend was tested using the nonparametric Kendall's tau, using programs developed by Reckhow et al. (1993) and Helsel et al. (2006). The Kendall's tau test is suitable for water quality data that show a non-normal distribution, contain missing data, and have censored values below method detection or reporting limits (Gilbert, 1987; Hirsch and Slack, 1984). The Kendall's tau statistic can also be modified to address seasonality.

The Kendall's tau test is based on a rank order statistic. That is, it compares ranks rather than actual data values. Observations are ordered by date (assuming seasonality is not present) and the difference between successive pairs of observations is calculated. The Kendall's tau statistic is based on the number of positive versus negative differences from successive pairs to determine if the data set is increasing or decreasing over time. When seasonality exists, data are grouped by season for comparisons, often with each month representing a separate season. An increasing trend exists when significantly more data pairs increase than decrease; a decreasing trend exists when significantly more data pairs decrease than increase; and if pairs decrease and increase at the same frequency, no trend exists (Newell et al., 1993).

Trend testing was done on flow-adjusted monthly data sets for all stream stations, except station 18003 (BO083), where flow data were generally not available. The null hypothesis tested was that there was no temporal trend in concentration of water quality constituents. The level of significance used to test the null hypothesis was 0.05. The slope calculated from the flow-adjusted concentrations (residuals) gives the magnitude of the trend and is interpreted as the change in concentration per year on a natural log scale. The slope in original units was computed on the natural log scale and calculated on an annual basis as follows (Helsel and Hirsch, 2002):

$$\% \text{ change/year} = (e^{b1} - 1)*100$$

Where “e” is the base of the natural logarithm and approximately equals 2.7183; and “b1” is the slope for the natural log-transformed data on an annual basis.[6]

Trend Analysis Results

Routine Grab Data

To account for variations over time, trend results are presented by end year for the past twelve years, with a focus on the most current end year, 2022. In comparing between end years, routine grab data usually indicated similar positive or negative trends, if significant, regardless of end year, although the slope representing the percent change per year often varied (Tables 7–11). Slopes representing the percent change per year frequently decreased with increasing end year. In some instances, slopes representing the percent change per year have become less negative with increasing end year. Less negative slopes with end year are apparent at stations 11956 (BO090) and 11954 (BO095) for PO_4-P. These patterns in slope over time may indicate step trends, in which reductions occurred at a given point in time; thus, the impact or slope decreases in magnitude with increasing time, or possibly reductions that occurred in the past that are now starting to increase.

For 2022, a significant decreasing trend was indicated at station 17226 (BO020), the most upstream site on the North Bosque River, for *E. coli*, NH_3-N, total-P, and PO_4-P (Table 7). The decreasing trend in PO_4-P was first detected in data associated with end year 2021.

Significant trends were indicated for all parameters but conductivity at station 11963 (BO040) located below Stephenville in 2022 (Table 8). Downward trends occurred with CHLA, *E. coli*, NH_3-N, PO_4-P, TKN, total-P, and TSS. Significant increasing trends occurred with NO_2-N+NO_3-N and total-N. For NO_2-N+NO_3-N at 11963 (BO040), increasing trends have been apparent since 2011, but only since 2015 for total-N. At station 11963 (BO040), NO_2-N+NO_3-N often comprises over 85% of the total-N in routine samples, which likely reflects contributions from the Stephenville WWTF discharge located about a quarter mile above station 11963 (BO040). With regard to the TMDL, significant decreasing trends for PO_4-P and total-P at station 11963 (BO040) were first detected with data through the end year 2007, which is a little over a year after the Stephenville WWTF started implementing phosphorus control practices as part of its treatment process.

Downward trends in PO_4-P and total-P also are reflected at station 11961 (BO070) on a similar timeframe to station 11963 (BO040) (Table 9). These downward trends were first noted with data analysis through 2008 for PO_4-P and through 2007 for total-P. At station 11961 (BO070), downward

---

[6] In several previous trend reports (i.e., McFarland and Millican, 2006; 2007; 2008; 2009; and 2010), the percent change was calculated as the percent change per month, although presented as the percent change per year and should be multiplied by 12 to obtain the percent change per year. In Tables 7 through 11 of this report, all slopes are provided as annual rates of change, including those obtained from previous reports.

trends occurred for all parameters but TKN, TSS and conductivity for data through 2022. Similar downward trends in nutrients have occurred since 2008 at 11961 (BO070), but only NH_3-N has consistently indicated downward trends for all end years evaluated.

At station 11956 (BO090), significant downward trends were indicated for *E. coli*, NO_2-N+NO_3-N, PO_4-P, TSS, and total-N (Table 10). In contrast, at station 11954 (BO095), decreasing trends for data through 2022 were reported only for NO_2-N+NO_3-N and PO_4-P (Table 11). An increasing trend was detected for NH_3-N and TKN for data through 2022 at station 11954 (BO095).

Results for 18003 (BO083) are presented separately from the other mainstem stations, because data for 18003 (BO083) were not flow adjusted (Table 12). Monitoring at station 18003 (BO083) also did not begin until 2003, representing a much shorter period of record than at any of the other stations. Of note, downward trends for NH_3-N and PO_4-P were significant but had a zero-slope value. A zero-slope estimate that is significant can occur using the Kendall's tau method when values have multiple ties, particularly if many values are at the reporting limit (McBride, 2000), which was the case for NH_3-N and PO_4-P at station 18003 (BO083). For data through 2022, a significant increasing trend was noted for conductivity (Table 12).

At station 13486 (GC100) located on Green Creek, trends were not analyzed for end years' 2011, 2013, or 2014 (Table 13). In 2011 and 2013, only one month (October 2011 and April 2013) had a routine grab sample, providing insufficient data for a meaningful annual trends update. In 2014, no routine water quality samples were collected at station 13486 (GC100), as conditions were dry or pooled at all visits. The 2022 data for 13486 (GC100) were not flow adjusted due to no streamflow conditions that persisted throughout the year. Trends evaluated through 2022 indicated significant decreases in all constituents except for total nitrogen (Table 13).

Table 7 Trend results for routine grab data for station 17226 (BO020)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
Conductivity	1997-2022	0.075	0.0857		1.3						-2.2	-3.1	-2.5		
CHLA	1997-2022	0.026	0.5574												
E. coli	1997-2022	-0.181	0.0001	-5.4	-4.8	-5.0	-4.7	-5.6	-4.9					-6.5	
NH_3-N	1997-2022	-0.096	0.0283	-1.1	-1.3	-1.7	-2.0	-2.4	-2.5	-2.5	-2.1				
NO_2-N+NO_3-N	1997-2022	-0.034	0.4337												
PO_4-P	1997-2022	-0.122	0.0055	-1.5	-1.2										
TKN	1997-2022	-0.060	0.1716					-1.1	-1.5	-1.3					
Total-P	1997-2022	-0.166	0.0002	-1.7	-1.6	-1.3	-1.5	-1.3	-1.5	-1.5					
TSS	1997-2022	0.061	0.1621								2.4	3.3	2.5		
Total-N	1997-2022	-0.032	0.4671												

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 8 Trend results for routine grab data for station 11963 (BO040)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
Conductivity	1997-2022	0.042	0.2468								-0.5	-0.6			
CHLA	1997-2022	-0.133	0.0003	-2.3	-2.2	-1.7	-1.6	-1.6	-2.5	-2.5	-2.7	-2.7			
E. coli	1997-2022	-0.196	0.0000	-4.1	-4.2	-4.3	-4.3	-3.9	-3.8	-3.4	-2.9				
NH_3-N	1997-2022	-0.136	0.0002	-2.4	-2.7	-3.2	-3.9	-4.3	-4.9	-5.1	-4.8	-4.2	-4.4	-5.6	-6.2
NO_2-N+NO_3-N	1997-2022	0.281	0.0000	3.4	3.3	3.3	2.9	2.9	3.0	2.9	2.9	2.4	2.6	2.5	2.0
PO_4-P	1997-2022	-0.421	0.0000	-6.2	-6.4	-6.0	-6.3	-6.4	-6.6	-6.9	-6.5	-7.1	-7.2	-7.7	-7.9
TKN	1997-2022	-0.234	0.0000	-2.1	-2.4	-2.5	-2.7	-2.9	-3.5	-3.5	-3.0	-2.8	-2.7	-3.0	-3.0
Total-P	1997-2022	-0.440	0.0000	-5.8	-5.9	-5.6	-5.8	-5.9	-6.2	-6.4	-6.0	-6.5	-6.7	-7.1	-7.1
TSS	1997-2022	-0.157	0.0000	-1.2	-1.2	-1.2	-1.4	-1.1	-1.2	-1.3					
Total-N	1997-2022	0.237	0.0000	1.9	1.7	1.6	1.1	1.1	1.0	1.0	1.1				

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 9 Trend results for routine grab data for station 11961 (BO070)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
Conductivity	1994-2022	-0.065	0.0737		-0.4	-0.4	-0.5	-0.8	-0.7	-0.8	-1.1	-1.1	-1.1	-1.2	-1.2
CHLA	1994-2022	-0.127	0.0006	-2.0	-1.9	-2.0	-2.0	-1.9	-2.4	-2.5	-2.7	-2.7	-3.4	-3.2	-2.4
E. coli	1994-2022	-0.096	0.0114	-2.2	-2.3	-2.2	-2.6	-2.5	-3.1	-3.3	-2.0		-3.1	-4.2	
NH_3-N	1994-2022	-0.114	0.0019	-0.8	-0.8	-1.1	-1.4	-1.8	-2.2	-2.5	-2.4	-2.2	-2.5	-2.9	-3.6
NO_2-N+NO_3-N	1994-2022	-0.100	0.0061	-1.9	-1.9	-2.1	-2.3	-2.6	-3.2	-3.1	-3.2	-3.2	-4.3	-4.6	-4.4
PO_4-P	1994-2022	-0.371	0.0000	-7.2	-7.2	-7.3	-7.3	-7.2	-7.3	-7.3	-6.6	-7.0	-7.4	-7.2	-5.5
TKN	1994-2022	-0.060	0.1053		-0.7	-0.8	-0.9	-1.1	-1.4	-1.4	-1.0				
Total-P	1994-2022	-0.298	0.0000	-3.3	-3.3	-3.6	-3.8	-3.9	-4.3	-4.6	-4.4	-4.7	-5.3	-5.5	-4.5
TSS	1994-2022	-0.035	0.3517												
Total-N	1994-2022	-0.095	0.0102	-0.8	-1.0	-1.2	-1.3	-1.5	-1.9	-1.8	-1.5	-1.5	-1.8	-1.8	-1.6

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; Millican and Adams 2020, 2021, 2022).

Table 10 Trend results for routine grab data for station 11956 (BO090)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
Conductivity	1996-202	0.014	0.7117								-0.4				
CHLA	1996-2022	-0.060	0.1146												
E. coli	1996-2022	-0.156	0.0000	-3.3	-2.9	-3.5	-3.4	-3.0	-2.6	-2.6			-2.8	-3.8	-4.1
NH_3-N	1996-2022	-0.034	0.3665			-0.5	-0.9	-1.1	-1.3	-1.7	-2.0	-2.2	-2.5	-2.8	-3.6
NO_2-N+NO_3-N	1996-2022	-0.156	0.0000	-2.9	-2.4	-2.1	-1.9	-2.6	-2.6	-3.4	-4.4	-3.7	-2.7		
PO_4-P	1996-2022	-0.122	0.0012	-1.1	-1.3	-1.5	-1.5	-1.3	-1.8	-2.0			-1.9	-2.7	-3.6
TKN	1996-2022	-0.062	0.0972		-0.7	-1.0	-1.2	-1.8	-2.3	-2.3	-1.9	-1.9	-1.6	-1.7	-2.5
Total-P	1996-2022	0.001	0.9860												
TSS	1996-2022	-0.116	0.0021	-1.4	-1.2	-1.5	-1.7	-1.5	-1.7	-2.1	-1.4	-1.5	-1.7	-2.2	-2.7
Total-N	1996-2022	-0.166	0.0000	-1.4	-1.3	-1.5	-1.6	-2.1	-2.5	-2.7	-2.8	-2.7	-2.3	-2.2	-3.0

a. Results for year 2021.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 11 Trend results for routine grab data for station 11954 (BO095)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	**Period Evaluated**	**Kendall Test Statistic**[a]	**p-value**[a]	**End Year 2022**	**End Year 2021**	**End Year 2020**[b]	**End Year 2019**[b]	**End Year 2018**[b]	**End Year 2017**[b]	**End Year 2016**[b]	**End Year 2015**[b]	**End Year 2014**[b]	**End Year 2013**[b]	**End Year 2012**[b]	**End Year 2011**[b]
Conductivity	1996-2022	0.048	0.2008												
CHLA	1996-2022	-0.015	0.6900												
E. coli	1996-2022	-0.041	0.2821				-1.8							-3.4	
NH_3-N	1996-2022	0.092	0.0149	0.7	0.9									-1.5	-2.3
NO_2-N+NO_3-N	1996-2022	-0.126	0.0008	-1.9	-1.4			-1.4			-1.8		-2.4	-2.4	
PO_4-P	1996-2022	-0.111	0.0032	-0.8	-1.0	-1.2	-1.3	-1.2	-1.4	-1.6	-1.1	-1.8	-2.4	-3.4	-4.4
TKN	1996-2022	0.075	0.0471	0.7											-1.8
Total-P	1996-2022	0.044	0.2384											-0.7	-1.0
TSS	1996-2022	-0.059	0.1156												-2.9
Total-N	1996-2022	-0.031	0.4145												

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 12 Trend results for routine grab data for station 18003 (BO083)

Data were transformed using a natural log transformation prior to trend analysis. Flow data were not available for this station, so water quality data were not flow-adjusted prior to trend evaluation. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic^a	p-value^a	End Year 2022	End Year 2021	End Year 2020^b	End Year 2019^b	End Year 2018^b	End Year 2017^b	End Year 2016^b	End Year 2015^b	End Year 2014^b	End Year 2013^b	End Year 2012^b	End Year 2011^b
Conductivity	2003-2022	0.163	0.0005	0.8	0.6	0.6									
CHLA	2003-2022	-0.013	0.7832				3.1	4.4	5.9	7.3	7.9	11.4	10.9	12.1	14.4
E. coli	2003-2022	0.026	0.5866												
NH_3-N	2003-2022	0.113	0.0092	0.0	0.0	0.0^c				0.0	-0.0	-0.0	-0.0	-0.0	-0.0
NO_2-N+NO_3-N	2003-2022	-0.010	0.8043												
PO_4-P	2003-2022	-0.155	0.0006	0.0	0.0	0.0					-0.0	-2.8	-1.8		
TKN	2003-2022	0.075	0.1116		1.7	2.1	2.6	2.6	2.6	3.1	3.0			5.4	5.5
Total-P	2003-2022	0.062	0.1871												4.4
TSS	2003-2022	0.006	0.8977				2.5	3.5	4.8	5.1	6.0	7.2	5.7	6.8	8.1
Total-N	2003-2022	0.062	0.1885			2.1	2.9	2.7	2.6	3.4					5.1

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

c. The percent slope change for NH_3-N is significant, but estimated as 0.00 percent change per year due to multiple ties or readings at the reporting limit.

Table 13 Trend results for routine grab data for major tributary station 13486 (GC100)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic^a	p-value^a	End Year 2022	End Year 2021	End Year 2020^b	End Year 2019^b	End Year 2018^b	End Year 2017^b	End Year 2016^b	End Year 2015^b	End Year 2014^b	End Year 2013^b	End Year 2012^b	End Year 2011^b
Conductivity	1993-2022	-0.191	0.0001	-0.6	-0.8	-0.9	-0.9	-1.2	-1.2	-1.3	-1.9	NA^c	NA	-1.9	NA
CHLA	1996-2022	-0.117	0.0268	-2.1	-3.0	-3.2	-3.1	-3.3	-4.1	-4.5	-5.7	NA	NA	-5.8	NA
E. coli	1995-2022	-0.153	0.0042	-3.7	-3.1	-4.1	-4.0	-3.3	-4.0	-5.3	-4.7	NA	NA		NA
NH_3-N	1993-2022	-0.093	0.0441	0.0	-0.7	-1.0	-1.3	-1.7	-2.2	-2.4	-2.7	NA	NA	-2.6	NA
NO_2-N+NO_3-N	1993-2022	-0.192	0.0000	-2.6	-2.3	-2.0						NA	NA		NA
PO_4-P	1993-2022	-0.231	0.0000	-3.9	-3.0	-3.1	-3.5	-3.2	-4.2	-4.4	-4.2	NA	NA	-5.3	NA
TKN	1995-2022	-0.122	0.0094	-1.2					-1.5			NA	NA		NA
Total-P	1995-2022	-0.200	0.0000	-2.4								NA	NA		NA
TSS	1995-2022	0.156	0.0008	-1.5		-1.3	-1.5	-1.3	-1.4	-2.0	-1.9	NA	NA		NA
Total-N	1993-2022	-0.089	0.0580		-1.4	-1.7	-1.3					NA	NA		NA

a. Results for year 2022. Due to no flow conditions throughout the year data for 2022 was not adjusted for flow.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019, and Millican and Adams 2020, 2021, 2022).

c. NA indicates not applicable. Trend analysis was not conducted for station 13486 (GC100) due to insufficient routine grab data in 2011, 2013, and 2014.

Volume-Weighted Data

Except for NO_2-N+NO_3-N and total-N at station 11963 (BO040), no increasing trends were indicated at any of mainstem stations for the volume-weighted data analyzed through 2022, but several decreasing trends occurred (Tables 14-19). At station 17226 (BO020), significant decreasing trends were indicated for all constituents (Table 14). Decreasing trends were indicated at 11963 (BO040) for NH_3-N, PO_4-P, TKN, total-P, and TSS (Table 15). Stations 11961 (BO070) and 11956 (BO090) indicated significant decreasing trends for all constituents (Tables 16 and 17). At station 11954 (BO095), significant decreasing trends were indicated for NO_2-N+NO_3-N, PO_4-P, total-P, TSS, and total-N (Table 18). There was no streamflow at station 13486 (GC100) on Green Creek during the entire year of 2022. This lack of streamflow data for station 13486 (GC100) prohibited the evaluation of trends for volume weighted data for end year 2022.

Table 14 Trend results for monthly volume-weighted data for station 17226 (BO020)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
NH_3-N	1997-2022	-0.221	0.0000	-3.0	-3.0	-3.2	-3.6	-4.2	-4.2	-5.0	-4.5	-4.7	-5.0	-4.9	-4.9
NO_2-N+NO_3-N	1997-2022	-0.135	0.0006	-2.6	-2.1							-2.6	-2.7	-4.8	-4.8
PO_4-P	1997-2022	-0.112	0.0045	-1.0	-1.0	-0.9	-1.1	-1.1	-1.0						
TKN	1997-2022	-0.244	0.0000	-2.1	-2.1	-2.1	-2.0	-2.2	-2.2	-1.9	-1.3				
Total-P	1997-2022	-0.233	0.0000	-2.3	-2.2	-2.1	-2.1	-2.0	-1.8	-1.7					
TSS	1997-2022	-0.221	0.0000	-5.6	-5.4	-5.6	-4.5	-4.1	-3.1						
Total-N	1997-2022	-0.210	0.0000	-1.9	-1.7	-1.6	-1.4	-1.7	-1.5	-1.4	-1.3		-1.3	-1.6	-1.6

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 15 Trend results for monthly volume-weighted data for station 11963 (BO040)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
NH_3-N	1994-2022	-0.182	0.0000	-2.7	-3.2	-3.7	-4.4	-4.6	-4.8	-5.1	-5.0	-4.7	-5.3	-6.7	-6.5
NO_2-N+NO_3-N	1994-2022	0.205	0.0000	2.6	2.5	2.6	2.1	2.7	2.5	2.2	1.4				
PO_4-P	1994-2022	-0.387	0.0000	-5.0	-5.1	-5.1	-5.3	-5.5	-5.7	-6.1	-6.1	-6.6	-7.2	-7.9	-7.6
TKN	1994-2022	-0.237	0.0000	-2.0	-2.3	-2.6	-2.6	-2.5	-2.6	-2.5	-1.9	-1.2	-1.1		
Total-P	1994-2022	-0.415	0.0000	-4.7	-4.8	-4.8	-4.9	-4.9	-5.0	-5.1	-5.0	-5.0	-5.3	-5.4	-5.2
TSS	1994-2022	-0.166	0.0000	-3.4	-3.4	-3.9	-3.4	-2.5			1.0	2.8	3.2	4.0	3.9
Total-N	1994-2022	0.145	0.0001	1.0	0.8			0.8	0.8						

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 16 Trend results for monthly volume-weighted data for station 11961 (BO070)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	**Period Evaluated**	**Kendall Test Statistic**[a]	**p-value**[a]	**End Year 2022**	**End Year 2021**	**End Year 2020**[b]	**End Year 2019**[b]	**End Year 2018**[b]	**End Year 2017**[b]	**End Year 2016**[b]	**End Year 2015**[b]	**End Year 2014**[b]	**End Year 2013**[b]	**End Year 2012**[b]	**End Year 2011**[b]
NH_3-N	1993-2022	-0.185	0.0000	-1.8	-1.8	-2.2	-2.5	-2.8	-3.0	-3.5	-3.3	-3.2	-3.9	-4.7	-4.5
NO_2-N+NO_3-N	1993-2022	-0.141	0.0001	-2.2	-2.2	-2.3	-2.2	-2.3	-2.4	-2.2	-2.2	-2.2	-3.8	-3.3	-3.3
PO_4-P	1993-2022	-0.354	0.0000	-6.2	-6.3	-6.2	-6.2	-5.8	-5.7	-5.5	-4.8	-4.9	-5.9	-4.7	-4.6
TKN	1993-2022	-0.149	0.0000	-1.5	-1.7	-1.7	-1.7	-1.6	-1.5	-1.4			-1.4	-1.6	-1.5
Total-P	1993-2022	-0.307	0.0000	-3.8	-3.9	-4.0	-3.9	-3.6	-3.6	-3.5	-2.9	-2.7	-4.0	-3.2	-3.1
TSS	1993-2022	-0.158	0.0000	-3.6	-3.6	-3.8	-3.2								
Total-N	1993-2022	-0.173	0.0000	-1.5	-1.7	-1.8	-1.8	-1.7	-1.7	-1.5			-1.8	-1.9	-1.9

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017; 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 17 Trend results for monthly volume-weighted data for station 11956 (BO090)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	**Period Evaluated**	**Kendall Test Statistic**[a]	**p-value**[a]	**End Year 2022**	**End Year 2021**	**End Year 2020**[b]	**End Year 2019**[b]	**End Year 2018**[b]	**End Year 2017**[b]	**End Year 2016**[b]	**End Year 2015**[b]	**End Year 2014**[b]	**End Year 2013**[b]	**End Year 2012**[b]	**End Year 2011**[b]
NH_3-N	1996-2022	-0.081	0.0239	-0.8	-1.2	-1.5	-2.3	-2.6	-3.1	-3.5	-3.7	-3.7	-4.1	-5.3	-5.1
NO_2-N+NO_3-N	1996-2022	-0.189	0.0000	-2.8	-2.0	-1.7	-1.9	-2.5	-2.2	-2.5	-2.2	-2.9	-2.4	-2.5	-2.5
PO_4-P	1996-2022	-0.168	0.0000	-1.8	-2.0	-2.2	-2.3	-2.3	-2.3	-2.4				-2.5	-2.4
TKN	1996-2022	-0.122	0.0007	-1.3	-1.4	-1.6	-2.0	-2.3	-2.4	-2.3					-1.8
Total-P	1996-2022	-0.125	0.0005	-1.3	-1.6	-1.8	-1.8	-1.6	-1.2	-1.1					
TSS	1996-2022	-0.223	0.0000	-4.4	-4.4	-4.7	-4.4	-4.2	-2.5						
Total-N	1996-2022	-0.214	0.0000	-1.9	-1.8	-1.9	-2.2	-2.5	-2.6	-2.6	-2.0	-1.9	-1.7	-2.8	-2.8

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 18 Trend results for monthly volume-weighted data for station 11954 (BO095)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
NH_3-N	1996-2022	0.055	0.1356					-1.3	-1.4	-1.8	-1.9	-2.0	-2.4	-4.1	-4.2
NO_2-N+NO_3-N	1996-2022	-0.098	0.0074	-1.2									-1.8		
PO_4-P	1996-2022	-0.162	0.0000	-1.5	-1.8	-2.1	-2.5	-2.5	-2.9	-3.1	-2.0	-2.3	-3.3	-5.6	-5.5
TKN	1996-2022	-0.063	0.0853		-0.9	-1.0								-2.8	-3.0
Total-P	1996-2022	-0.140	0.0001	-1.4	-1.9	-2.1	-2.1	-1.9	-1.8	-1.9			-1.5	-2.6	-2.6
TSS	1996-2022	-0.217	0.0000	-4.7	-5.2	-5.2	-4.6	-4.1	-3.4	-3.1				-5.5	-5.5
Total-N	1996-2022	-0.126	0.0005	-1.0	-1.1	-0.9	-0.9	-1.0						-1.4	-1.5

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

Table 19 Trend results for monthly volume-weighted data for major tributary station 13486 (GC100)

Data transformed using a natural log transformation and adjusted for flow prior to trend analysis. Significant slopes indicated at a p-value of 0.05.

Parameter	Period Evaluated	Kendall Test Statistic[a]	p-value[a]	End Year 2022	End Year 2021	End Year 2020[b]	End Year 2019[b]	End Year 2018[b]	End Year 2017[b]	End Year 2016[b]	End Year 2015[b]	End Year 2014[b]	End Year 2013[b]	End Year 2012[b]	End Year 2011[b]
NH_3-N	1993-2022	NA	NA	NA[c]	-1.7	-2.0	-2.2	-2.7	-3.0	-1.8	-2.8	NA	NA	-2.1	NA
NO_2-N+NO_3-N	1993-2022	NA	NA	NA	-3.8	-3.8	-2.4					NA	NA	4.5	NA
PO_4-P	1993-2022	NA	NA	NA	-4.6	-5.1	-4.7	-4.2	-4.3	-2.1	-2.5	NA	NA		NA
TKN	1993-2022	NA	NA	NA	-2.7	-2.7	-2.2	-2.2	-1.7			NA	NA		NA
Total-P	1993-2022	NA	NA	NA	-2.2	-2.3	-1.9	-2.0				NA	NA		NA
TSS	1993-2022	NA	NA	NA	-5.4	-6.0	-4.9	-3.8				NA	NA		NA
Total-N	1993-2022	NA	NA	NA	-2.3	-2.2	-1.6	-1.4			2.2	NA	NA	4.1	NA

a. Results for year 2022.

b. Summary of significant trend slopes (McFarland and Millican 2012; McFarland and Adams 2013, 2014a, 2015, 2016, 2017, 2018; Millican, Adams, and McFarland 2019; and Millican and Adams 2020, 2021, 2022).

c. NA indicates not applicable. Trend analysis was not conducted for station 13486 (GC100) due to a lack of loading data in 2011, 2013, 2014, and 2022.

Evaluation of Stream Water Quality Goal Attainment

Three approaches were used to evaluate attainment of the TMDL water quality goals as presented in the I-Plan (TCEQ and TSSWCB, 2002). The first approach plotted annual average flow versus annual average PO_4-P concentrations of routine samples for more recent years compared to pre-TMDL regression relationships. The second approach compared annual average PO_4-P concentrations of routine grab to target concentrations or goals set for index stations in the TMDLs. The third approach compared data acquired post-implementation of the TMDL to a set of probability distribution curves constructed from TMDL model predictions.

Regression Relationships

To evaluate if the relationship between PO_4-P and flow has changed over time, a set of regression equations was derived from historical data for 1996 through 2000 representing each of the five index stations for pre-TMDL conditions (TCEQ and TSSWCB, 2002). These regression equations relate annual average concentrations of SRP from routine grab samples (y-axis values) to the base-10 logarithm of annual average stream flow (x-axis values) and were developed in the I-Plan using data from the following stations:

- Station 17226 (BO020) for the index station above Stephenville
- Station 11963 (BO040) for the index station below Stephenville
- Station 11958 (BO085) for the index station above Meridian
- Station 11956 (BO090) for the index station at Clifton
- Station 17605 (BO100) combined with data from station 11954 (BO095) for the index station at Valley Mills

Due to changes in monitoring locations, some additional data were used in development of these regression relationships. Monitoring at station 11958 (BO085) was discontinued in April 2005, and data from station 18003 (BO083) were used in combination with data from station 11958 (BO085). While station 18003 (BO083) is located about 11.6 river miles upstream of station 11958 (BO085), it is considered more representative of the index station defined in the I-Plan as above Meridian. Flow was not measured at either 11958 (BO085) or 18003 (BO083) on a continuous basis, so annual average flows from station 11956 (BO090) were used in the equations presented in the I-Plan and in the current evaluation. As previously noted for trend analysis, data for stations 17605/11954 (BO100/BO095) were also combined. Station 11961 (BO070), while not an index station, had long-term data that were evaluated in a similar manner for comparison.

Of note, the regression equations comparing PO_4-P concentrations versus annual average flow differ somewhat from those presented in the I-Plan and early annual reports for a couple of reasons. First, annual average flows were revised based on the most updated rating curve and stage data information. For this report, regression equations were also included using data from the post-TMDL period of 2001-2022. In addition, grab samples used in the analysis were scrutinized to ensure samples were representative of routine monitoring, with relatively equal time intervals between samples throughout the year as suggested in the I-Plan (TCEQ and TSSWCB, 2002). By including only samples representative of relatively equal time intervals, several samples associated with special studies were dropped that had been included in previous analyses. Previously, all available PO_4-P data for grab samples had been included regardless of the time interval between samples. Using samples separated by relatively equal time intervals decreases the bias that may occur if sampling was more frequent during a particular time of year. Extended periods of pooling or no flow in association with the relatively dry summer months still caused unequal sampling intervals in some years, particularly at station 17226 (BO020), which more often has pooled conditions.

In comparing data in this manner to evaluate goal attainment, annual average PO_4-P concentrations below the pre-TMDL regression line were considered indicative of potential improvements in water quality, while annual average PO_4-P concentrations plotted above the pre-TMDL regression line were considered indicative of potentially worsening conditions (Figures 5-10). There is some variability expected, as these regression relationships are not perfect, but they provide a tool for general assessment of changes in water quality, taking variability in flow conditions into consideration.

At the most upstream index station, 17226 (BO020) located above Stephenville, only 10 out of 22 years clearly indicated annual average concentrations of PO_4-P below the pre-TMDL regression line (Figure 4). The highest annual average concentrations of PO_4-P reported at station 17226 (BO020) occurred during 2014, when annual average flow was among the lowest recorded at this location. In contrast, the high annual average flows in 2015 and 2016 had PO_4-P concentrations below the pre-TMDL regression line. The influence of these drought or low-flow years and wet or high-flow years is also apparent in the post-TMDL regression line, which shows a decrease in concentration as annual average flows increase. Of note, the annual average flow recorded for 2022 at station 17226 (BO020) represents the lowest annual average flow recorded for the entire evaluation period. However, concentrations of PO_4-P remained below the pre-TMDL regression line.

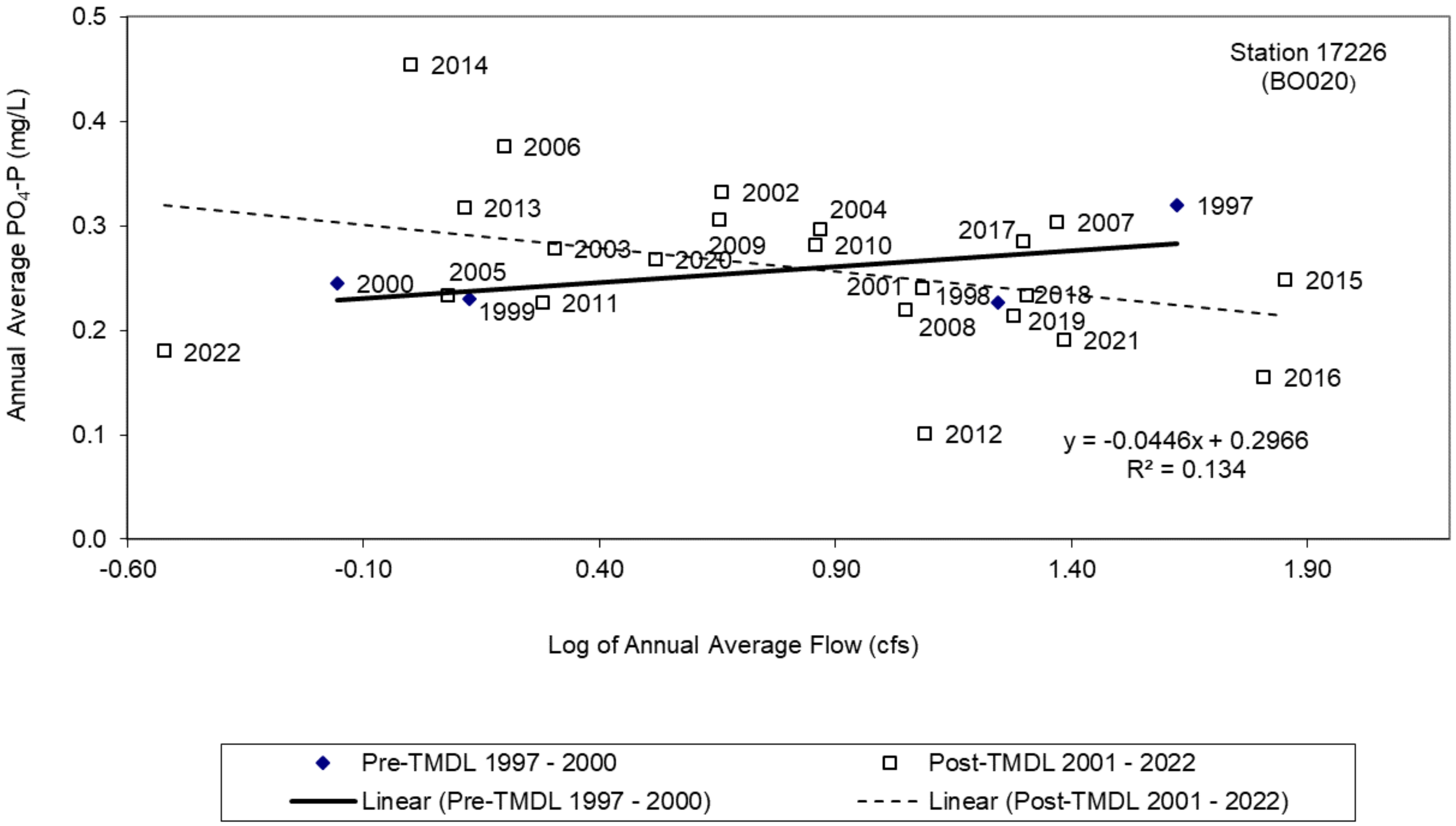

Figure 4 Relationship of the natural log of flow to annual average PO_4-P concentration of routine grab samples for station 17226 (BO020)

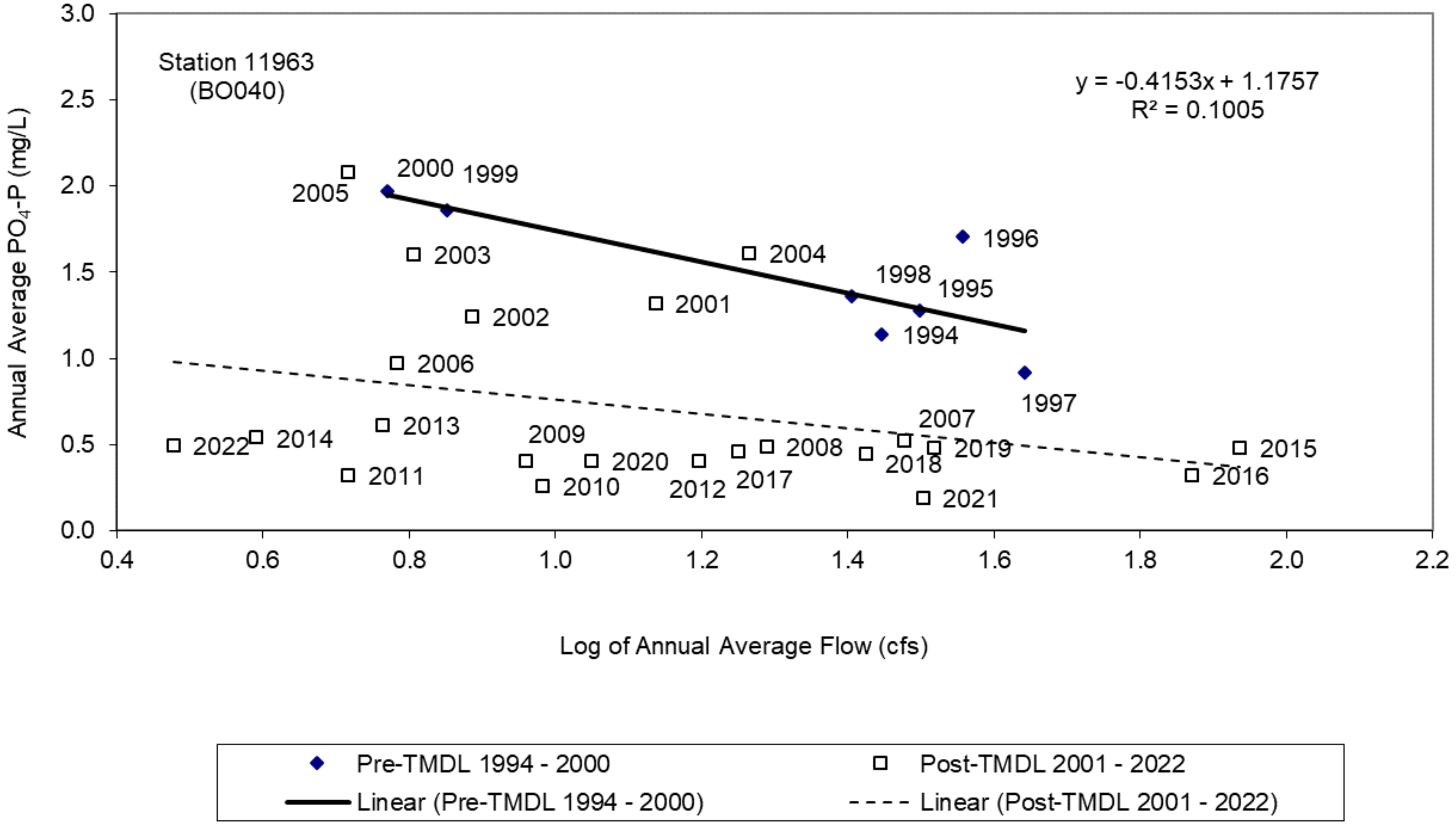

Figure 5 Relationship of the natural log of flow to annual average PO_4-P concentration of routine grab samples for station 11963 (BO040)

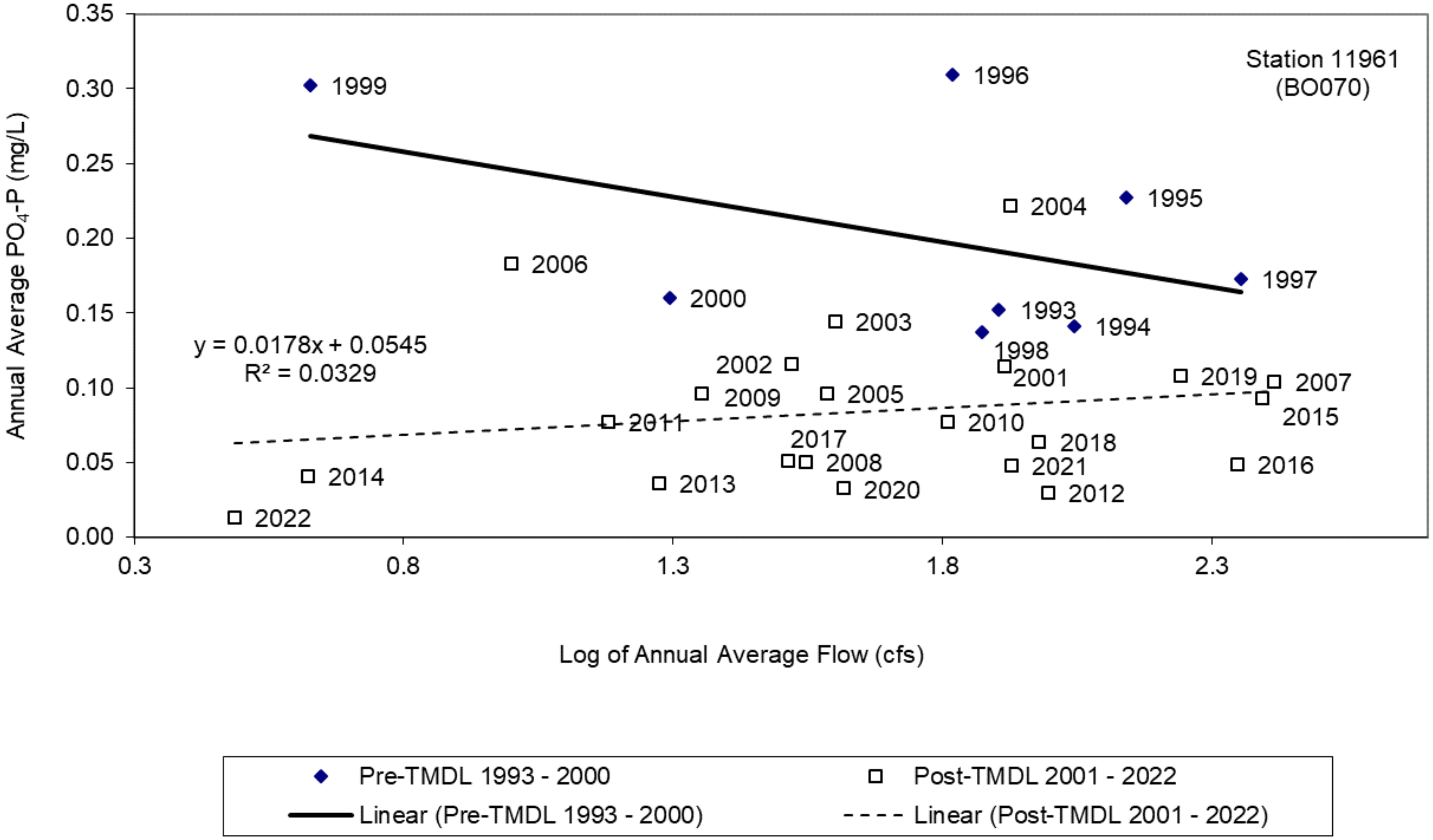

Figure 6 Relationship of the natural log of flow to annual average PO_4-P concentration of routine grab samples for station 11961 (BO070)

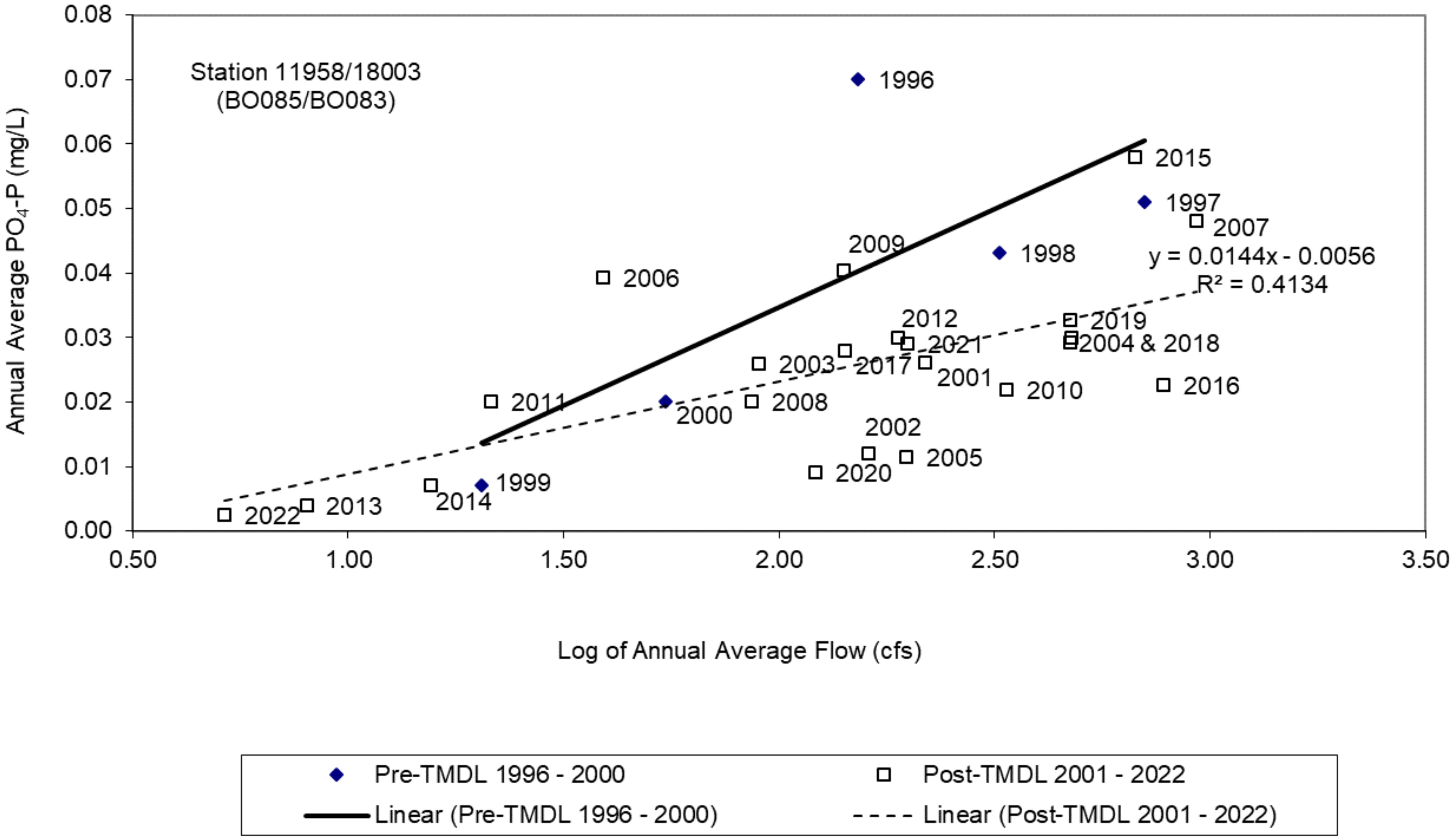

Figure 7 Relationship of the natural log of flow to annual average PO_4-P concentration of routine grab samples for station 11958/18003 (BO085/BO083)

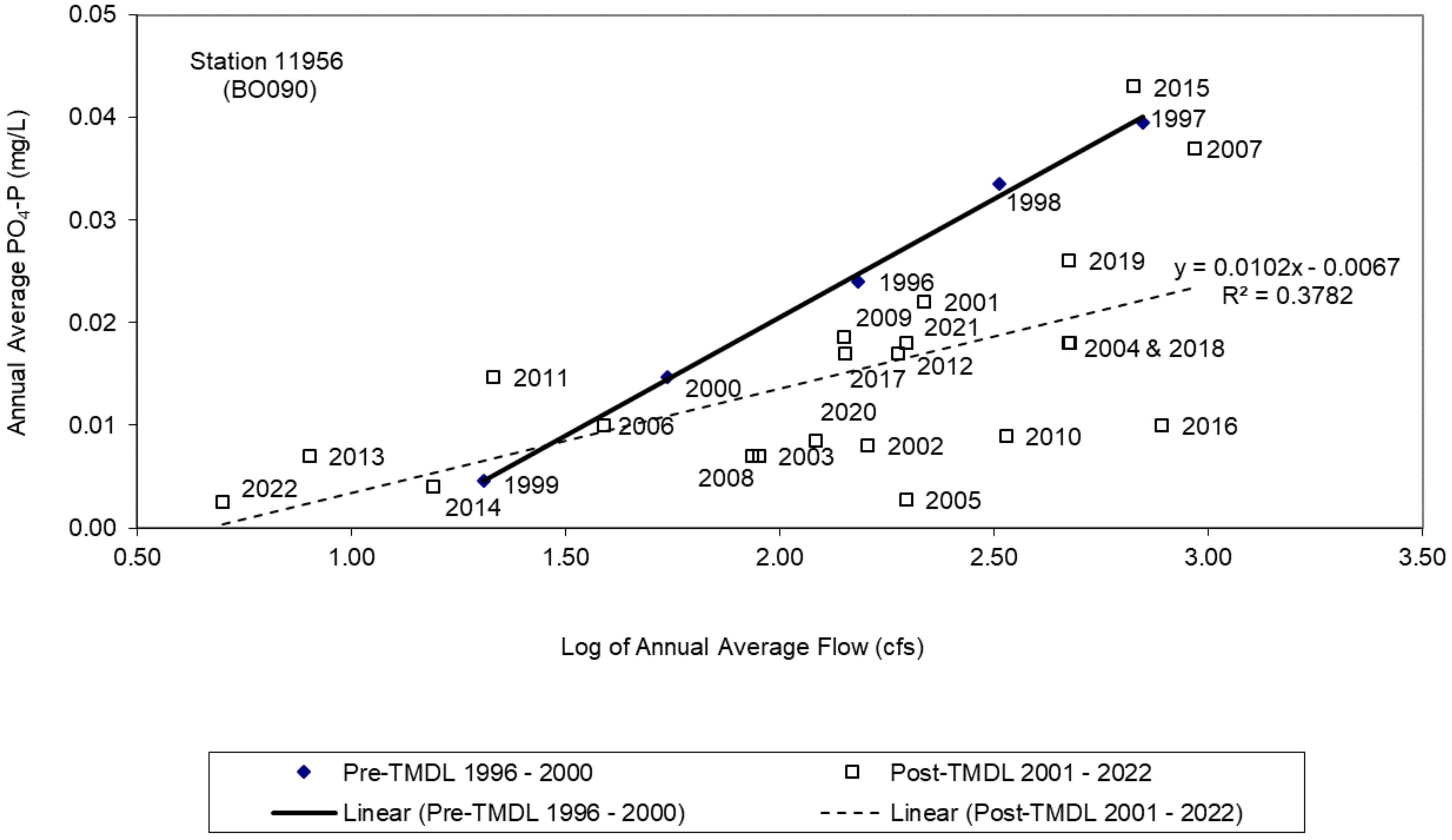

Figure 8 Relationship of the natural log of flow to annual average PO_4-P concentration of routine grab samples for station 11956 (BO090)

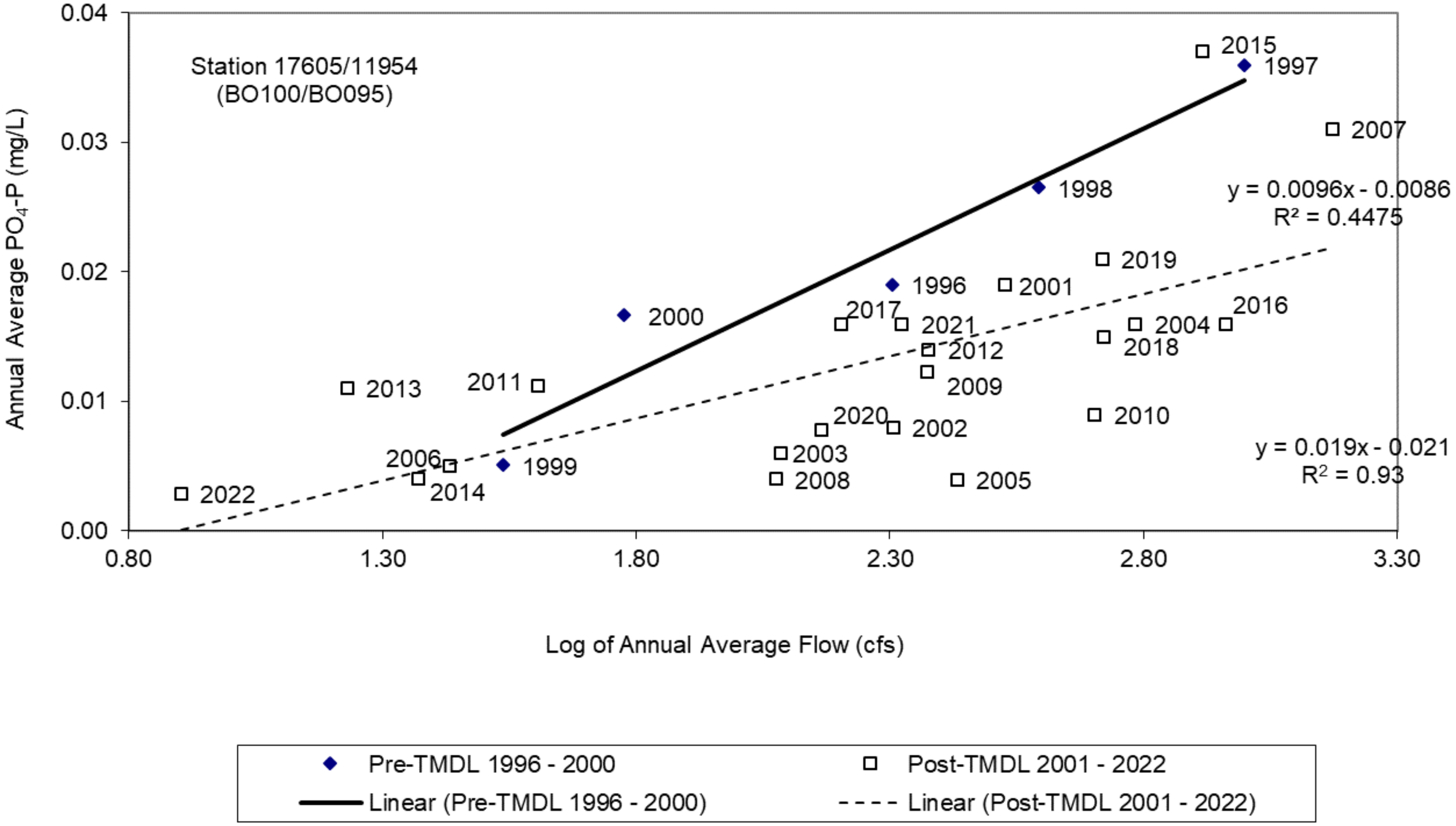

Figure 9 Relationship of the natural log of flow to annual average PO_4-P concentration of routine grab samples for station 17605/11954 (BO100/BO095)

The station below Stephenville, 11963 (BO040), indicated annual average PO_4-P concentrations below the pre-TMDL line in all but two post-TMDL years (Figure 5). Only in 2004 and 2005 were concentrations slightly above the pre-TMDL regression line. Station 11963 (BO040) is located just below Stephenville about a quarter mile downstream of the major outfall for the Stephenville WWTF. The decreasing relationship of PO_4-P concentrations with increasing flows is indicative of dilution of a point source or constant contribution in both the pre-TMDL and post-TMDL regression lines. In the fall of 2005, the Stephenville WWTF started implementing phosphorus control practices, which correlates with a large decrease in the PO_4-P concentration of routine grab samples post 2005 for this location. Similar to station 17226 (BO020), the highest annual average flows occurred in 2015 and 2016, but extrapolating the pre-TMDL regression line still indicated annual average PO_4-P concentrations below this line. For 2022, PO_4-P concentrations were below the pre-TMDL regression line.

While station 11961 (BO070) near Hico is not an index station, it is representative of conditions between index stations 11963 (BO040) and 11958/18003 (BO085/BO083). Station 11961 (BO070) is about 22.5 river miles downstream of station 11963 (BO040) and about 27.8 miles above station 18003 (BO083). In comparing annual average PO_4-P concentrations to the pre-TMDL line with annual average flow, only 2004 indicated annual average PO_4-P concentrations above the pre-TMDL regression line (Figure 6). While the slope is not as steep, station 11961 (BO070) also has a pre-TMDL regression line similar to station 11963 (BO040), with PO_4-P concentrations decreasing with increasing flows. This likely reflects the point source influence of contributions from the Stephenville WWTF at this downstream location. The post-TMDL regression line is essentially flat, which may indicate a significant reduction in point source contributions. For 2022, PO_4-P concentrations were well below the pre-TMDL regression line at station 11961 (BO070).

Moving downstream, the combined stations 11958/18003 (BO085/BO083) have annual average PO_4-P concentrations below the pre-TMDL regression line most years (Figure 7). Exceptions with concentrations above the pre-TMDL regression line occurred in 2006, 2009, 2011, 2013, and 2022. In 2022, annual average flow conditions were at the lowest measured for this station. While the 2022 annual average PO_4-P concentration is slightly above the pre-TMDL regression line, the actual annual average concentration was at the reporting limit of only 0.0025 mg/L. The post-TMDL regression line indicates a similar relationship to flow and PO_4-P concentrations as compared to the pre-TMDL regression.

At stations 11956 (BO090) and 17605/11954 (BO100/BO095), along the lower portion of the North Bosque River, very similar responses occurred, likely due to the close proximity of these two locations (Figures 8 and 9). Station 11956 (BO090) is only about 10 river miles upstream of station 11954 (BO095), with one major tributary, Neils Creek, flowing in between these two stations. At these downstream locations, values above the pre-TMDL regression line generally occurred in years representing either very low or very high flows.

Annual average PO_4-P concentrations at stations 11956 (BO090) and 17605/11954 (BO100/BO095) were above the pre-TMDL regression lines in the low-flow years of 2011, 2013, and 2022 and the high-flow year of 2015 (Figures 8 and 9). In 2014, which was another very low-flow year, annual average PO_4-P concentrations at station 11956 (BO090) were above the pre-TMDL regression line, but just along the line at station 17605/11954 (BO100/BO095) when extrapolated. In 2016, which was another high-flow year like 2015, PO_4-P concentrations were well below the pre-TMDL regression lines for both locations. This shift in the relationship between PO_4-P concentrations for 2015 and 2016 likely reflects a flushing effect of two very wet years occurring back-to-back. As at station BO083, the post-TMDL regression lines for BO090 and BO095 indicate similar relationships to flow and PO_4-P concentrations, with concentrations increasing with flow.

Annual Average TMDL Goal

The second approach used to evaluate goal attainment was to compare the annual average concentration to the long-term predicted concentration from the TMDL modeling effort and the target concentration for each index station (TNRCC, 2001). Comparing the annual average of routine grab samples shows the TMDL goal has been reached on occasion at all five stations (Figures 10 and 11), but not consistently at all locations.

Of note, the comparisons shown in Figures 10 and 11 are similar to graphs shown in the annual status report provided by TCEQ (e.g., TCEQ, 2021), but the timeframe represented differs. In the graphs presented in the TCEQ status report, the annual timeframe represents a water year (October through September) rather than a calendar year (January through December). The calendar year is presented herein for consistency with charts comparing annual average PO_4-P concentrations with annual average flow (Figures 4-9) and the presentation of data in previous trend reports by TIAER (e.g., McFarland and Millican, 2012). Despite these time differences, annual PO_4-P concentrations follow a similar pattern to those in TCEQ status reports (TCEQ, 2021).

Annual PO_4-P concentrations at station 17726 (BO020) were often above the TMDL goal, with concentrations dipping below the goal only in 2012 (Figure 10). In 2021 and 2022, the annual average PO_4-P concentration was above the goal, but slightly below the long-term predicted concentration.

A very notable drop in PO_4-P concentrations occurred at station 11963 (BO040) from 2005 to 2006, coinciding with implementing phosphorus control practices at the Stephenville WWTF in the fall of 2005 (Figure 10). Annual average concentrations at station 11963 (BO040) have remained below or only slightly above the target level since 2007. Drought conditions, as occurred in 2013 and 2014, are suspected to have caused increased concentrations in these years as decreased ambient stream flow was mixing with effluent from the Stephenville WWTF. In 2022, the annual average concentration was above the target concentration of 0.448 mg/L. An unusually high PO_4-P concentration was recorded in January 2022. The elevated concentration from that one event coupled with a decreased monitoring frequency resulted in an annual PO4-P concentration that was greater than what has been recorded over the previous fifteen years.

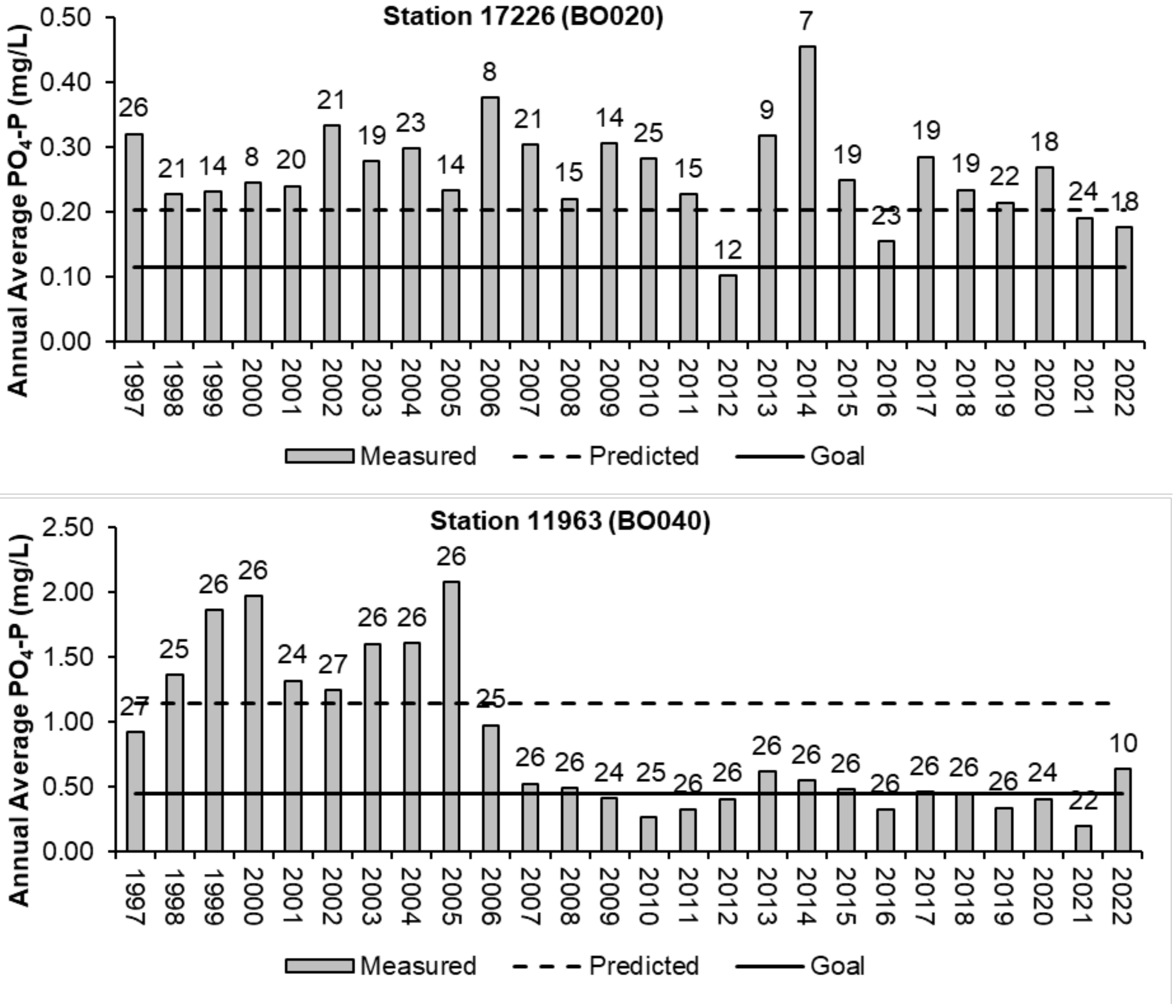

Figure 10 Annual average PO_4-P from routine grab data for stations 17226 (BO020) and 11963 (BO040) compared to the long-term predicted concentration without TMDL implementation and the TMDL goal

Values above bars represent the number of samples in each year.

At station 11958/18003 (BO085/BO083), concentrations have been below the TMDL goal in all years but 2015 (Figure 11). The relatively high annual average concentration of PO_4-P in 2015 followed two years of drought (2013 and 2014), when very low flows and low PO_4-P concentrations occurred (see Figure 7). In contrast to 2013 and 2014, 2015 was a year with very high flows. Flows in 2016 were comparable to 2015, but the lower concentrations in 2016 are likely due to a flushing of the system from having two very wet years back-to-back. Since 2016, PO_4-P concentrations have been below target levels.

In the post-TMDL period, evaluating data from 2000 through 2022, annual average concentration exceeded the goal at stations 11956 (BO090) and 17605/11954 (BO100/BO095) in 2007 and 2015 (Figure 11). Both 2007 and 2015 were years with unusually high annual average flows that followed years with low flows (see Figures 8 and 9). In 2016, annual average concentrations of PO_4-P were much lower than would be predicted based on flow alone (Figures 8 and 9), again likely due to two very wet years occurring one after the other. In 2022, PO_4-P concentrations continued to be below target levels.

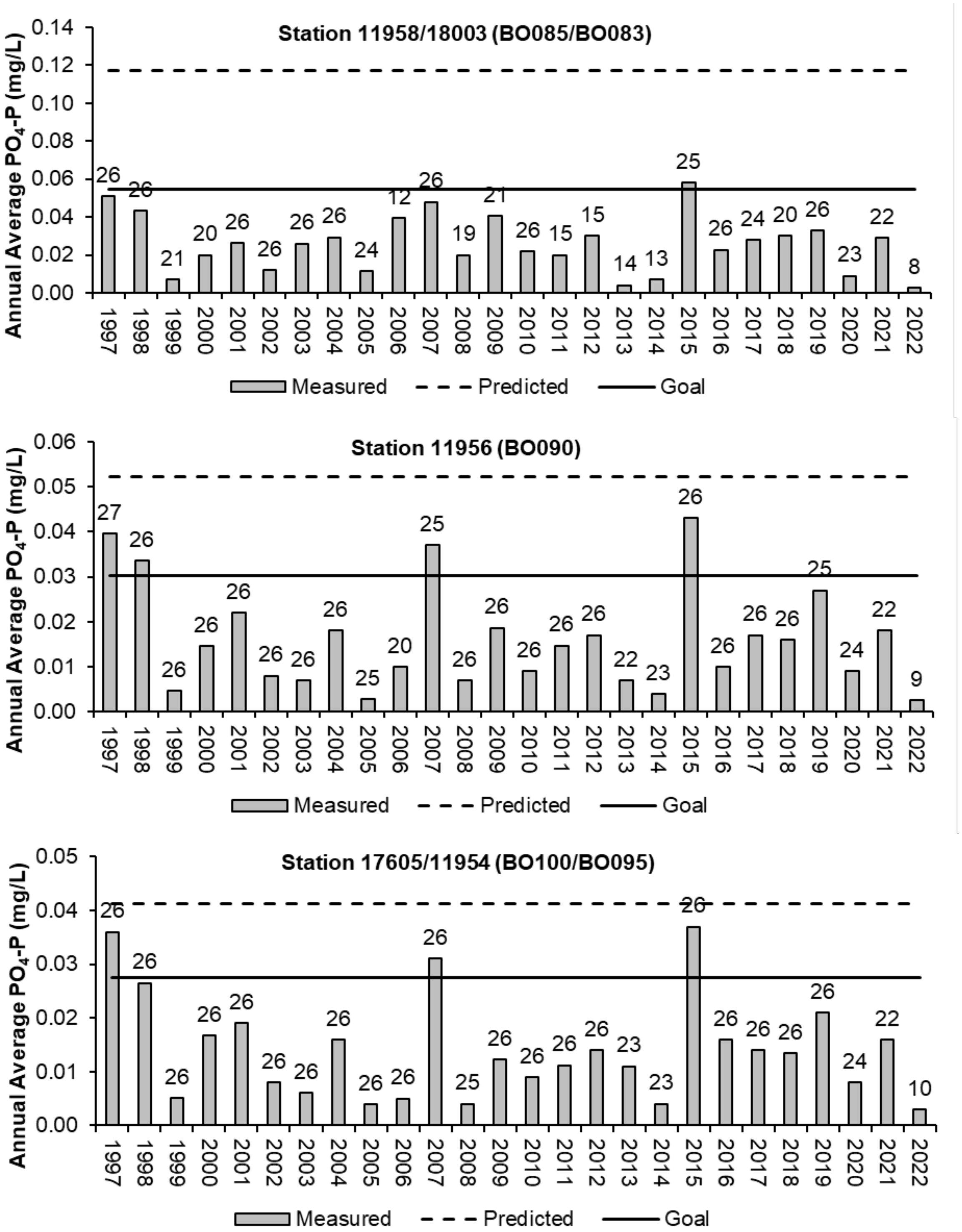

Figure 11 Annual average PO_4-P from routine grab data for stations 11958/18003 (BO085/BO083), 11956 (BO090), and 17605/11954 (BO100/BO095) compared to the long-term predicted concentration without TMDL implementation and the TMDL goal

Values above bars represent the number of samples in each year.

Probability Distribution Curves

The third approach used a set of probability distribution curves constructed from the TMDL modeling and within the I-Plan (TCEQ and TSSWCB, 2002). Comparison of these TMDL modeling curves ("TMDL-e" curves) to post-TMDL developed probability curves of annual average PO_4-P should indicate if water quality goals are being met. The post-TMDL probability curves presented are based on data from 2001 through 2022 (Figures 12-16). The I-Plan indicates the following for determining success based on these probability curves (TCEQ and TSSWCB, 2002):

- If the monitored data curve is entirely below the model-predicted TMDL-e curve, then the water quality goal is being attained.
- If the monitored data curve is entirely above the model-predicted TMDL-e curve, then the water quality goal is not being attained.
- Partial attainment occurs if the monitored data curve crosses the model-predicted TMDL-e curve.

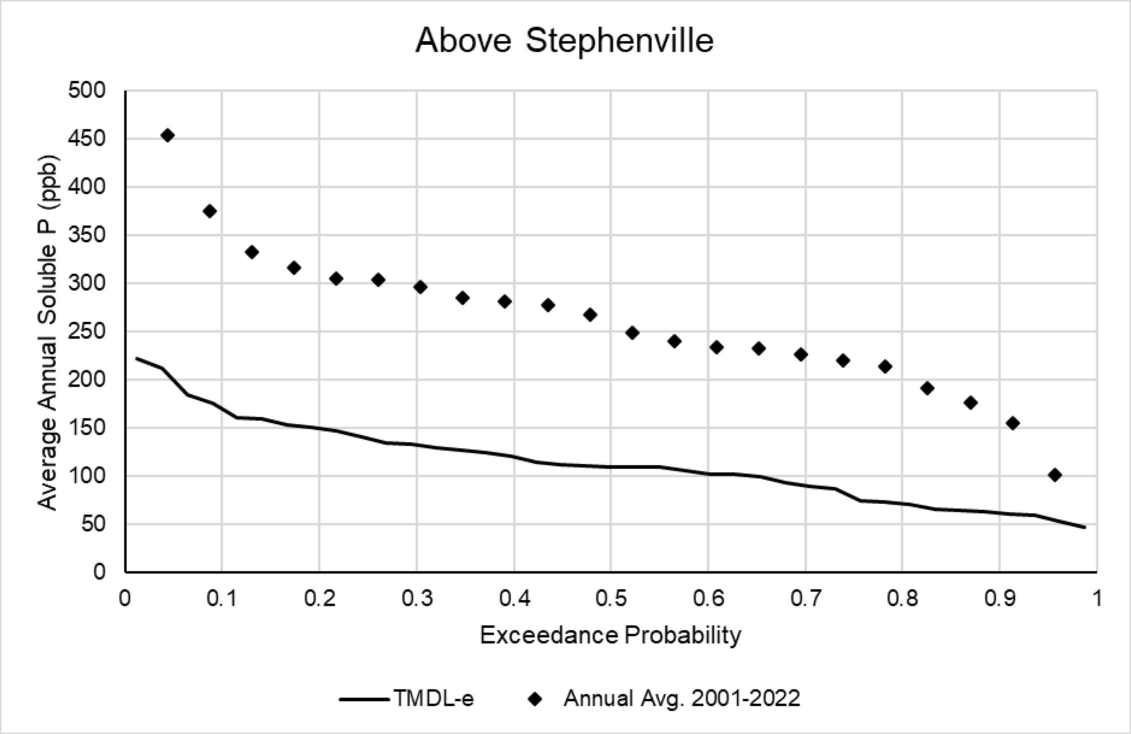

Figure 12 TMDL goal probability curve for index site above Stephenville (17226 [BO020]) compared to monitored data curve

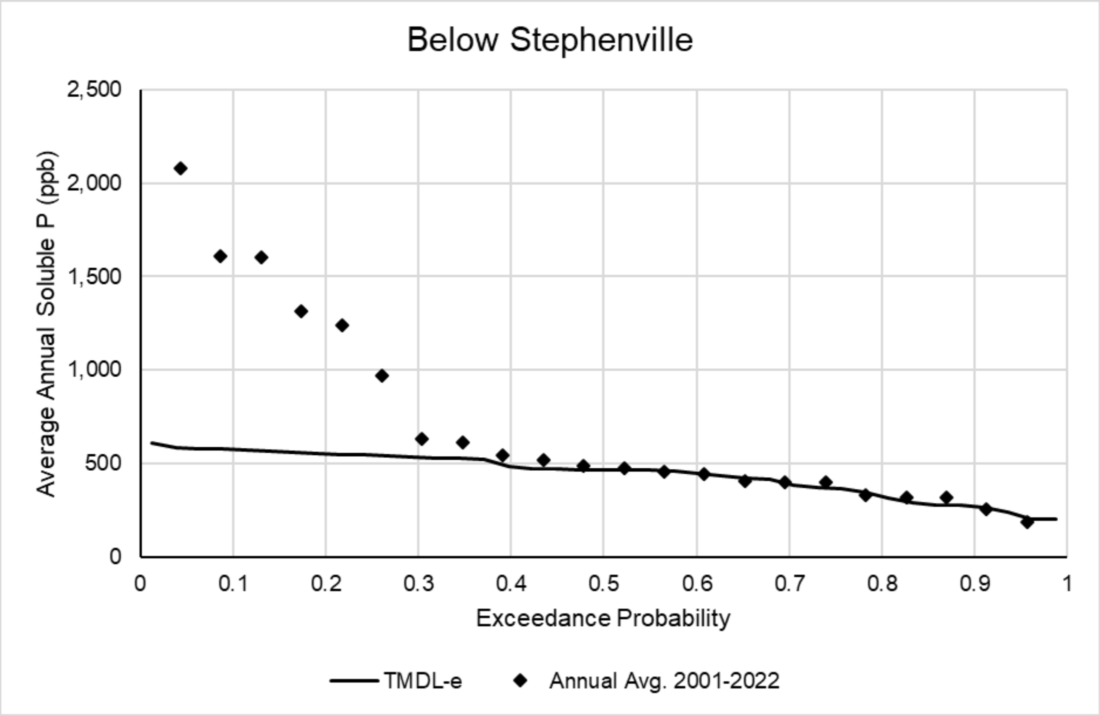

Figure 13 TMDL goal probability curve for index site below Stephenville (11963 [BO040]) compared to monitored data curve

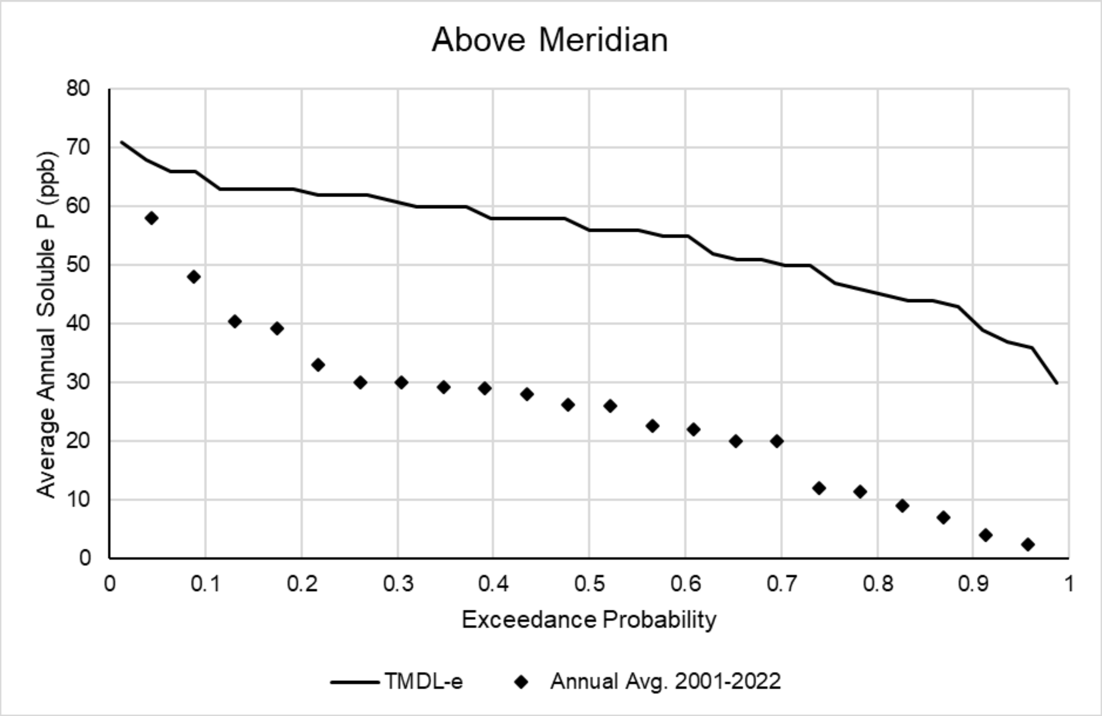

Figure 14 TMDL goal probability curve for index site above Meridian (18003 [BO083]) compared to monitored data curve

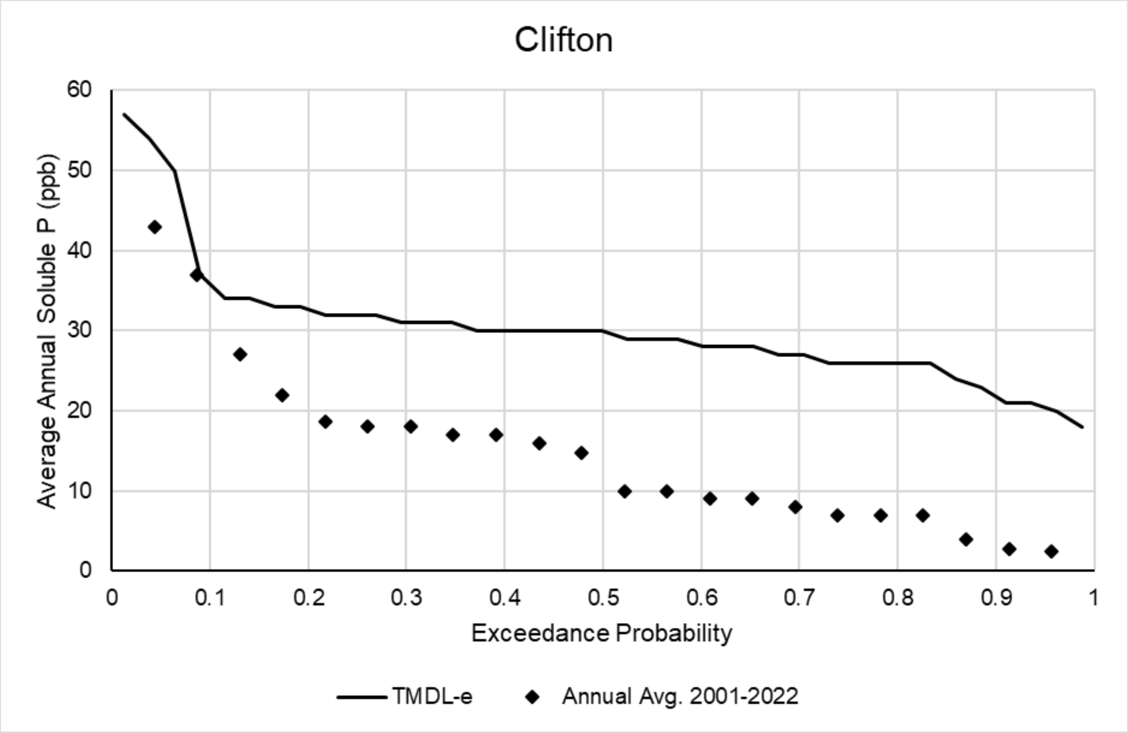

Figure 15 TMDL goal probability curve for index site at Clifton (11956 [BO090]) compared to monitored data curve

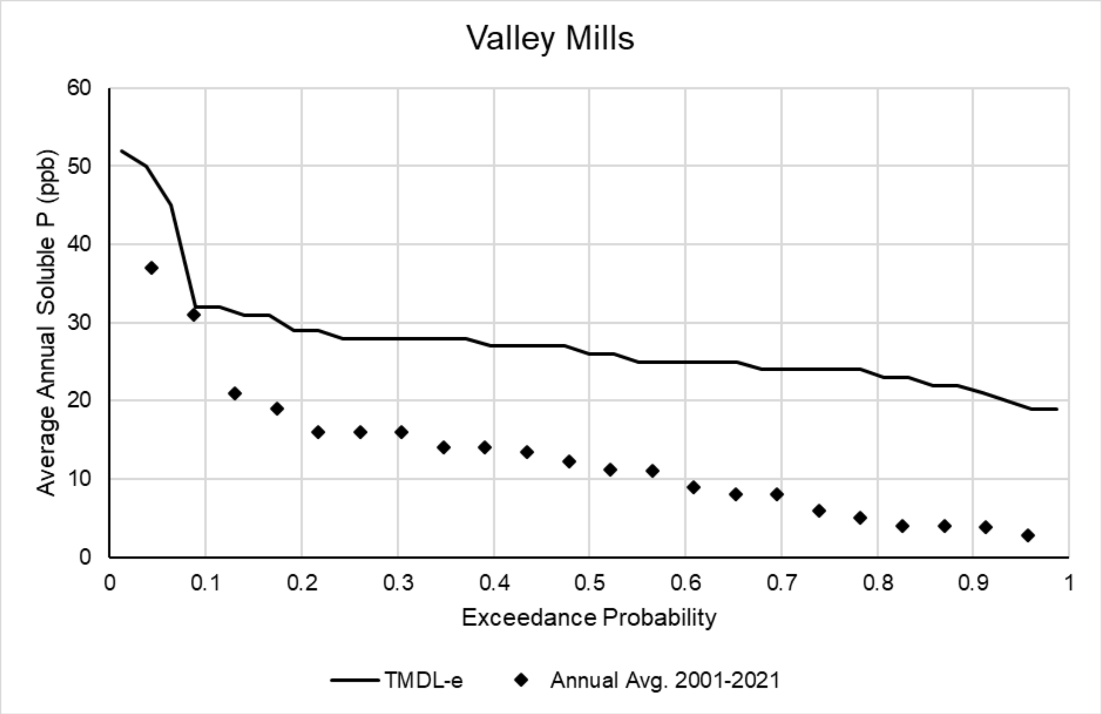

Figure 16 TMDL goal probability curve for index site at Valley Mills (11954 [BO095]) compared to monitored data curve

The following conclusions can be drawn from Figures 12–16:

- For station 17226 (BO020) above Stephenville (Figure 12), the TMDL goal is not being met, as the monitoring probability curve is entirely above the model-predicted curve.
- For station 11963 (BO040) below Stephenville (Figure 13), the monitoring curve comes very close to the model-predicted curve and contains four points that are slightly below it. At station 11963 (BO040), it is anticipated that with additional years, more instances of crossing the model-predicted curve will occur, particularly as the monitoring curve picks up more years associated with implementation of phosphorus control practices by the Stephenville WWTF.
- For station 18003 (BO083) above Meridian, attainment of water quality goals is indicated, with the entire monitored data curve falling below the model-predicted curve (Figure 14).
- For station 11956 (BO090) at Clifton, adequate attainment is indicated, with only one point located directly on the model-predicted curve and 95% of the monitored data below the model (Figure 15).
- For station 11954 (BO095) at Valley Mills, full attainment of water quality goals is indicated, with all points of the monitored data curve falling below the model-predicted curve (Figure 16).

Summary and Discussion

Results based on data through 2022 indicated several statistically significant decreasing trends in nutrients at stations within the North Bosque River watershed, although also a few increasing trends for some parameters. For PO_4-P and total-P, only significant decreasing trends were indicated. To help illustrate these trends, focusing on PO_4-P, box and whisker plots are presented of the flow-adjusted, volume-weighted results by year (see Figures 17-22). Within these plots, “3σ Limits” refers to data within three standard deviations of the mean, with “UCL” denoting the Upper Control Limit and “LCL” denoting the Lower Control Limit. “M” equals the average of annual medians, and “n” represents the number of months with data represented for each year. The solid lines shown connect the median values of each year. The length of the box represents the distance between the 25th and 75th percentiles and the vertical lines or “whiskers” extending from the box represent the annual minimum and maximum values of the flow-adjusted, volume-weighted PO_4-P concentration. The circles located within the box-and-whisker plots represent the annual mean value of the flow-adjusted, volume-weighted PO_4-P concentration. Small boxes plotted outside of the box-and-whisker plots are outlier values.

Similar box-and-whisker plots are shown in Appendix B for bacteria results. For bacteria, significant decreases were indicated for most stations based on routine monthly grab data, supporting the assertion within the I-Plan that practices implemented to decrease SRP should have some corollary effect in reducing bacteria loadings (TCEQ and TSSWCB, 2002).

With regard to SRP, decreasing trends in PO_4-P were indicated at all five index stations for routine grab data (Tables 7-8 and 10-12) and at the four index stations evaluated for volume-weighted data (Tables 14-15 and 17-18). Decreasing trends in PO_4-P were also indicated for routine grab and volume-weighted data at station 11961 (BO070) on the mainstem of the North Bosque River near Hico.

These decreasing trends in PO_4-P were similar to findings in previous reports (e.g., Millican, Adams, and McFarland, 2020 and Millican and Adams, 2021 and 2022). The decreasing trend at 17226 (BO020) is very subtle, representing a decrease of only about one percent per year for routine grab data and volume-weighted data (Tables 7 and 14, Figure 17).

At station 11963 (BO040), significant decreases in PO_4-P appear to be directly related to implementation of phosphorus control at the Stephenville WWTF in late 2005 (Figure 18). Phosphorus control at the Stephenville WWTF is probably also influencing the decreasing trends noted at station 11961 (BO070) further downstream (Figure 19). Box and whisker plots of monthly average concentrations by year at station 11963 (BO040) showed a notable decrease in median PO_4-P for 2006 through 2021 (Figure 18), with a somewhat similar decrease shown at station 11961 (BO070) in Figure 19.

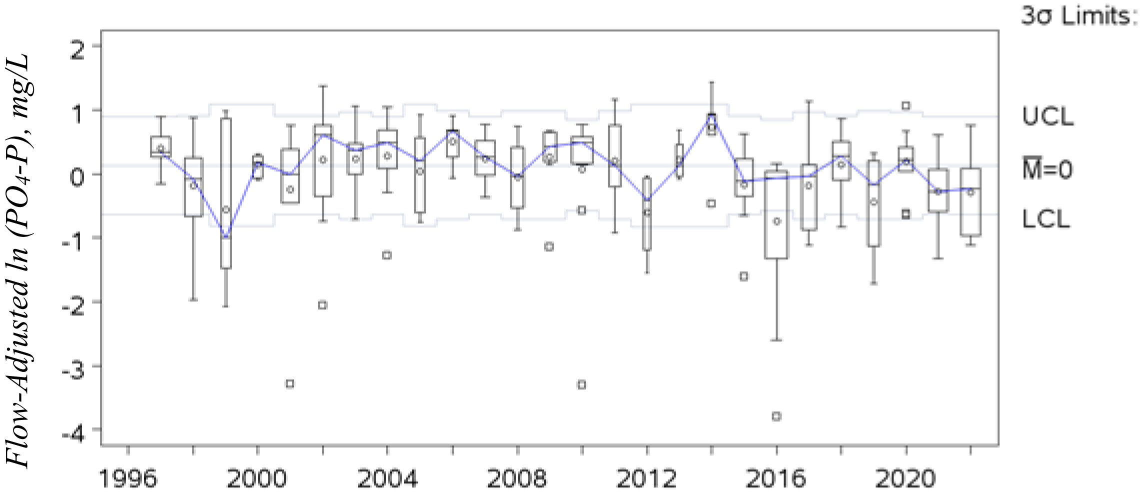

Figure 17 Annual box-and-whisker plots of monthly volume-weighted PO_4-P grab data for station 17226 (BO020)

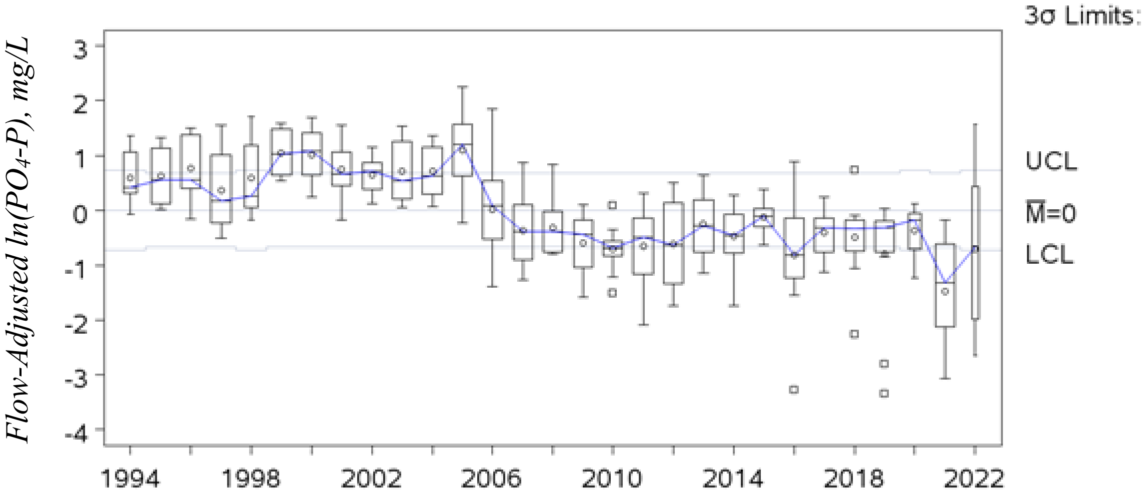

Figure 18 Annual box and whisker plots of monthly volume-weighted PO_4-P grab data for station 11963 (BO040)

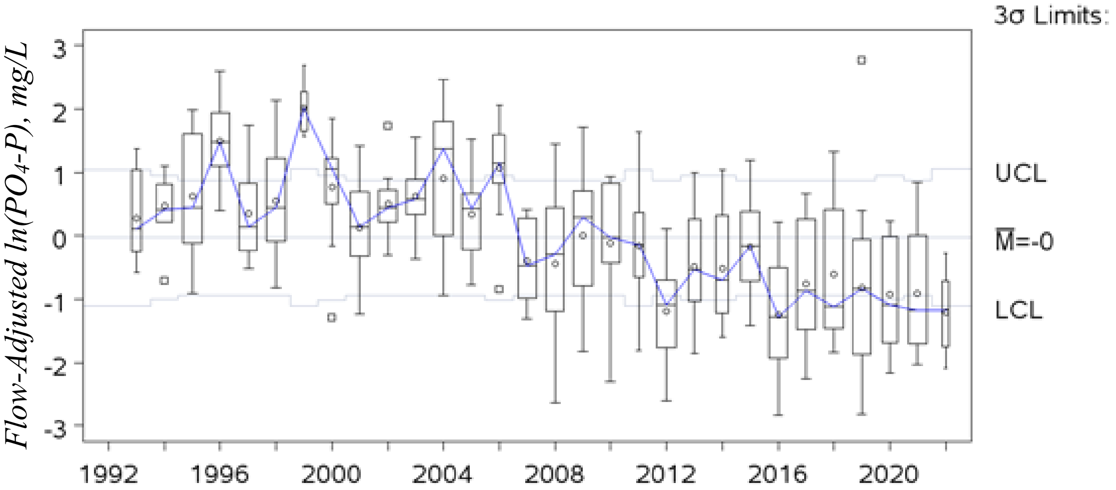

Figure 19 Annual box-and-whisker plots of monthly volume-weighted PO_4-P grab data for station 11961 (BO070)

A decrease in PO_4-P concentrations also occurred at more downstream stations (11956 [BO090] and 11954 [BO095]), but the timing of the initial decrease occurred in 1999 (Figures 20 and 21), prior to implementation of phosphorus control practices at either the Stephenville or Clifton WWTFs. Station 11954 (BO095) near Valley Mills is located below, and station 11956 (BO090) above, the Clifton WWTF discharge. These trends may be related to the handling of poultry litter from operations in the Neils Creek watershed and other drainages in the lower portion of the North Bosque watershed. As of 2006, 12 poultry facilities were operating in the lower portion of the North Bosque River watershed, primarily within the Meridian and Neils creeks watersheds (McFarland and Jones, 2006). These poultry operations have their litter collected by a composting company (Mida-Bio) and have not conducted onsite disposal since about 2000 (McFarland and Jones, 2006). A recent follow up found that Dr. Gobbler (parent company Mida-Bio), based in Clifton, Texas, still hauls turkey litter from area operations, creating and distributing Dr. Gobbler Soil R/X Organic Compost (Dr. Gobbler, 2022). This initial decrease in PO_4-P concentrations at stations in the lower portion of the watershed appears to correspond in part with this change in handling of poultry litter.

In a similar fashion, changes in waste management associated with the I-Plan impacting CAFOs and AFOs are expected to impact water quality trends along the North Bosque River. Most CAFOs and AFOs are or have been in the upper portion of the North Bosque River watershed (Figure 22). To evaluate land-use changes, information on regulated CAFOs was reviewed and used to develop a Geographic Information System (GIS) layer documenting the location of these facilities and associated WAFs as part of the TCEQ NPS Program Clean Water Act Section 319(h) project *Evaluating Effectiveness of Implementation Plan Activities within the North Bosque River Watershed* (McFarland and Adams, 2016). Metadata in the GIS layer for WAFs included crop type and dominant type of waste applied. This layer was updated under the current project to reflect new WAFs and those no longer in use (considered historical) based on permit changes effective through August 2022 (Figure 22).

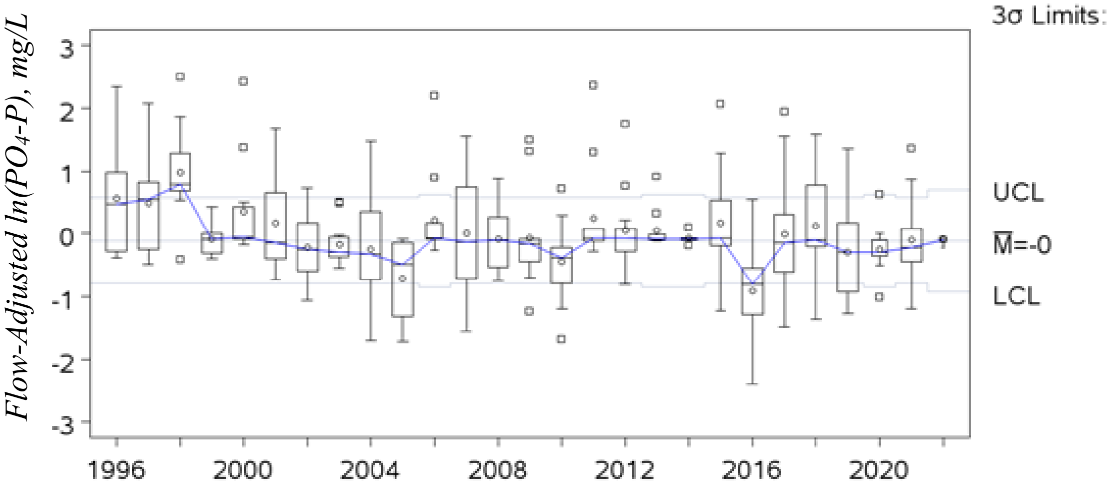

Figure 20 Annual box-and-whisker plots of monthly volume-weighted PO_4-P data for station 11956 (BO090)

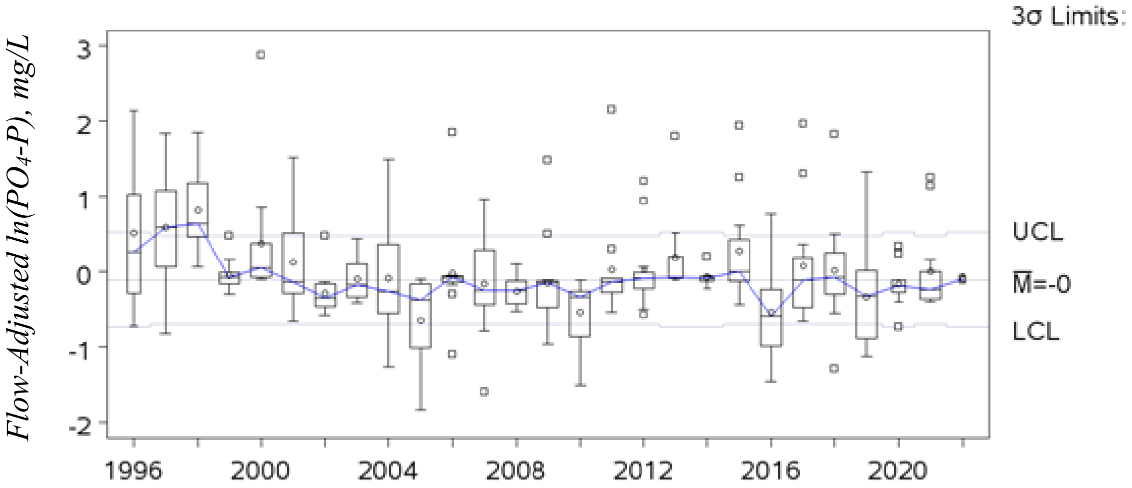

Figure 21 Annual box-and-whisker plots of monthly volume-weighted PO_4-P data for station 11954 (BO095)

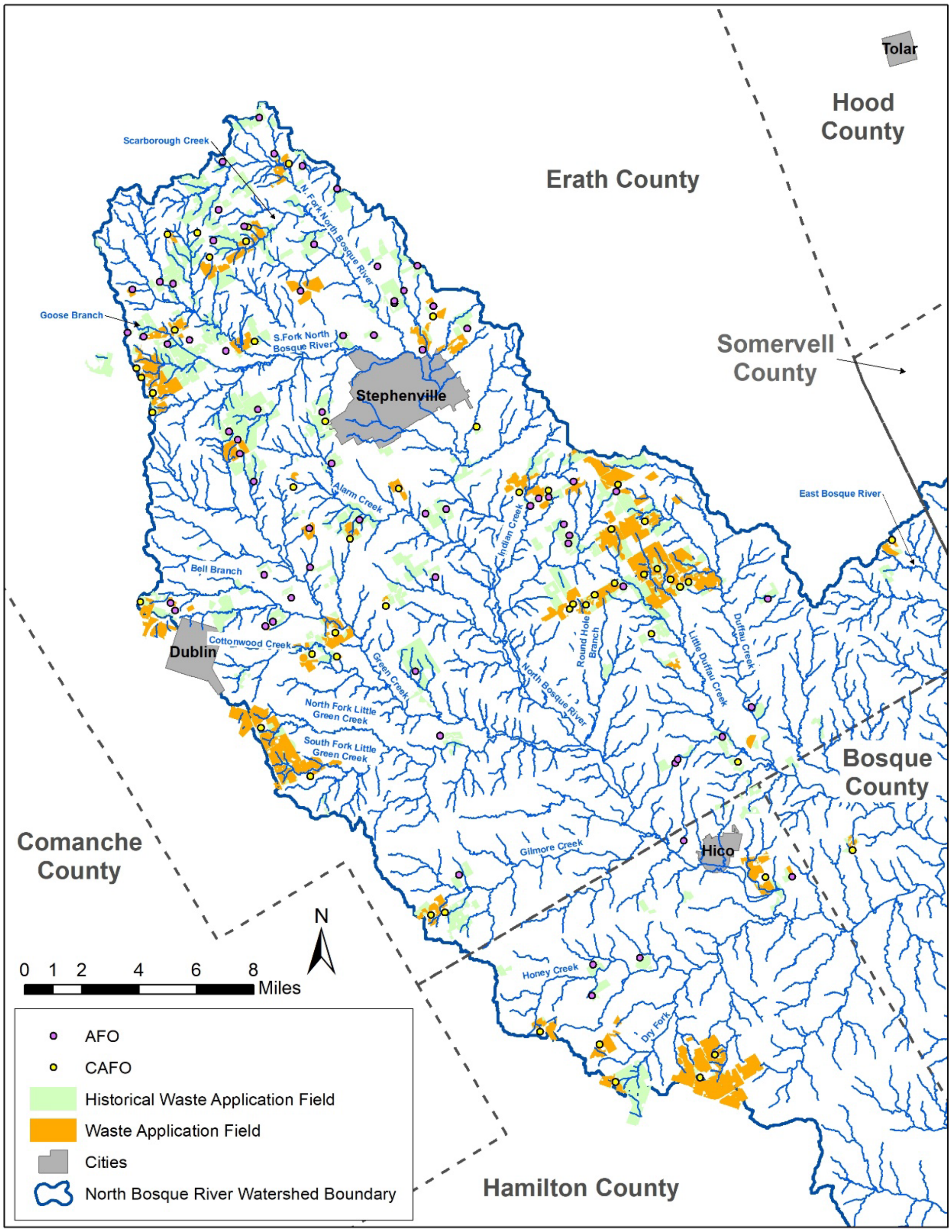

Figure 22 Map of CAFOs, AFOs, and associated WAFs (active and historical) within the North Bosque River watershed, representing conditions as of fall 2022

Map includes historical WAFs for the Microgy Biogas facility. Dots for CAFOs and AFOs, both active and inactive, are shown to give a general indication as to the type of operation (CAFO or AFO) associated with WAFs.

The location of most AFOs was originally determined from information from TCEQ or the Texas Department of State Health Services (DSHS), Division of Milk and Milk Products as part of a previous GIS effort focusing on conditions representing active operations as of 2005 and historical operations since 1995 (see McFarland and Jones, 2006). The 2005 GIS layer of facilities and WAFs was updated in 2007 for a modeling project for the North Bosque River watershed to include WAFs associated with the Microgy Biogas facility (Houser and Hauck, 2010). The designation of "historical" versus "active" WAFs for AFOs was based on the status of the operations in 2022, with fields associated with inactive operations designated as historical.

The information on active CAFO and AFO operations was reviewed in the fall of 2022 based on TCEQ inspection data and drive-by assessments. As noted earlier, about 45,000 dairy cows were estimated within the watershed in 2001 and about 43,000 in 2022. The watershed included 52 active operations in 2022, of which 44 were CAFOs. As of the fall of 2022, regulated CAFOs included 32 dairies, five heifer or calf raising operations, five feedlots, and two sale or auction barns. Of the eight AFOs in the watershed, two are dairies, one is a feedlot, and five are heifer or calf raising facilities.

From 2000 to 2022, a notable decrease in the land area categorized as active WAFs has occurred, more than offset by an increase in historical fields (Table 20). For 2022 and 2021, a relatively small decrease in land associated with active WAFs has occurred since 2020. This shift in land use indicates less land area in the watershed is being used for manure waste application and likely is having an impact on reductions indicated in stream phosphorus concentrations. The implementation of CNMPs and revised CAFO permit regulations requiring manure application at appropriate agronomic rates played an important role in facilitating this shift in land use, as fields high in soil phosphorus are no longer used for waste application.

Crop uptake of phosphorus is important to limiting runoff of phosphorus into streams, and Coastal bermudagrass is the dominant crop associated with WAFs (Table 21). These Coastal fields are often over-seeded with a winter grain crop. While soils, particularly in the headwaters, are often shallow, thus, not allowing the production of cropland, in some areas, a dual cropping system of sorghum and winter wheat is maintained. Rangeland or native grasses are also used for waste application, although not to the extent as in the past.

Many of the CAFOs have expanded or identified new fields for waste application with their permit renewals, in association with amendments to the CAFO rules adopted by TCEQ in 2014 (TCEQ, 2014). In addition, fields identified as active WAFs do not include areas where animal waste has been transferred to a third party for potential land application, although those who accept animal waste are expected to apply it at appropriate agronomic rates. Because contributions from WAFs were considered a major nonpoint source of SRP to the North Bosque River, decreases in the land area used for active WAFs can be considered partially responsible for the decreases noted in stream PO_4-P concentrations and loadings.

Table 20 Comparison over time of active and historical WAFs in the North Bosque River watershed

WAF Layer[b]	**Year**	**Active**[a]	**Historical**	**Total**
Acres	2000[b]	24,554	2,142	26,696
No. Fields	2000[b]	623	93	716
Acres	2005[b]	19,122	7,574	26,696
No. Fields	2005[b]	473	243	716
Acres	2012 & 2013[c]	15,693	18,215	33,908
No. Fields	2012 & 2013[c]	380	557	937
Acres	2014[c]	13,533	18,603	32,136
No. Fields	2014[c]	326	611	937
Acres	2015[c]	13,337	19,014	32,351
No. Fields	2015[c]	344	629	973
Acres	2016[d]	13,451	19,191	32,642
No. Fields	2016[d]	351	637	988
Acres	2017[d]	13,741	18,812	32,553
No. Fields	2017[d]	349	672	1,021
Acres	2018[d]	13,753	18,850	32,603
No. Fields	2018[d]	357	685	1,042
Acres	2019[d]	14,485	18,659	33,144
No. Fields	2019[d]	359	709	1,068
Acres	2020[d]	14,122	19,622	33,744
No. Fields	2020[d]	365	725	1,090
Acres	2021[d]	13,559	20,480	34,039
No. Fields	2021[d]	347	766	1,113
Acres	2022[d]	13,857	20,467	34,324
No. Fields	2022[d]	349	784	1,133

a. The acres and number of fields excludes 54 fields representing about 1,772 acres associated with the Microgy biogas plant. The Microgy biogas plant began operation in late 2007 and ceased operation in 2010. Microgy fields were excluded to allow representation of just the fields associated with CAFOs and AFOs.

b. Information on WAFs for 2000 and 2005 from McFarland and Jones (2006).

c. Source: McFarland and Adams (2015).

d. Represents updated review of WAF information based on permit changes effective between August and September of each state fiscal year.

Table 21 Summary of active and historical WAF information for CAFOs and AFOs in the North Bosque River watershed as of fall 2022

Primary Type of Waste Applied	Primary Crop	FY22 Estimated Active (acres)	FY22 Estimated Number of Active Fields	FY22 Estimated Historical (acres)	FY22 Estimated Number of Historical Fields
Liquid	Coastal/Small Grain	4,247	99	2,197	129
Liquid	Coastal	531	18	2,302	97
Liquid	Sorghum/Small Grain	497	11	155	19
Liquid	Sorghum	0	0	197	12
Liquid	Rangeland	80	4	14	3
Liquid	Other	547	11	0	0
Liquid	**Subtotal**	**5,902**	**143**	**4,866**	**260**
Solid	Coastal/Small Grain	5,654	134	4,193	168
Solid	Coastal	759	21	6,343	197
Solid	Rangeland	247	15	1,630	33
Solid	Sorghum/Small Grain	1,296	36	1,870	73
Solid	Sorghum	0	0	1,274	31
Solid	Other	0	0	290	22
Solid	**Subtotal**	**7,955**	**206**	**15,601**	**524**
Microgy	Microgy	0	0	1,772	54
	Total	**13,857**	**349**	**22,239**	**838**

Besides changes in land management, long-term weather patterns, particularly in precipitation, can have a notable impact on water quality trends. Precipitation has been variable over the analysis period for the watershed, as indicated by annual precipitation values for Stephenville and Waco (Figure 23). The 30-year annual average precipitation for Stephenville is 32.6 inches and 36.2 inches for Waco. For Stephenville, most years between 1993 and 1998 had precipitation amounts near or above the 30-year average, while 12 out of 23 years between 1999 and 2022 were below the 30-year average. Very wet years often followed very dry years, with well above normal precipitation occurring in 2004, 2007, and 2015. In contrast, 2016 represents a moderately wet year following a very wet year, 2015. Annual precipitation at Waco followed the same general pattern as at Stephenville, but with more annual precipitation generally reported for Waco.

An important consideration in interpreting the annual rainfall data is the pattern of rainfall within each year. For example, although total annual precipitation for 2012 and 2013 indicate near normal amounts, drought conditions occurred that reflect a cumulative precipitation deficit during this period (NCDC, 2014). By comparing monthly precipitation totals to monthly normal precipitation for Stephenville for the years 2010 through 2016, 64 out of 96 months had below normal precipitation (Figure 24). May 2015 was an extremely wet month, with 20.5 inches of rain reported, about 4.6 times the normal monthly precipitation of 4.4 inches. In 2021, annual rainfall was slightly above normal, with May and June being the wettest months, with a combined total of over 13.2 inches of rain in Stephenville. For 2022, ten consecutive months beginning in January had below average precipitation (Figure 24). The variability month to month within a given year has a larger impact on streamflow than total rainfall. These temporal changes in precipitation within years are reflected in the stream flow, with very low-flow conditions in 2013 and 2014 and the very high stream flows occurring in 2015 and 2016 at all monitoring stations throughout the watershed (Figure 25).

Comparisons of average PO_4-P concentrations for grab samples to the log of annual average flow generally supported trend analysis findings (Figures 4-9). Most post-TMDL years for stations showing significant downward trends had average PO_4-P concentrations below the pre-TMDL regression relationship. Weather extremes do appear to have an influence on meeting the TMDL goal and the evaluation of success, depending on how the goal is evaluated. While all five index stations indicated exceedances of the TMDL goal in 2015, comparing solely routine grab concentrations to target levels (Figures 10 and 11), the more upstream stations indicated concentrations within target levels when annual average flows were taken into consideration (Figures 4, 5, and 7). In 2016, annual average flows were comparable to 2015, but much lower PO_4-P concentrations occurred in 2016 at all stations. While 2015 was a wet year preceded by two very dry years, 2013 and 2014, 2016 was a moderately wet year preceded by a wet year, 2015. The annual average flow and PO_4-P at all stations during 2022 was the lowest recorded during both the pre-TMDL and post-TMDL periods. At the time of developing this report, drought conditions have persisted in the North Bosque River watershed. Based on the previously mentioned impact on PO_4-P concentrations as dry years transition into relatively wet years there is a possibility that concentrations will increase somewhat dramatically as rainfall and associated streamflow increase.

This report presents an annual update of trends in routine grab samples and loadings for stations within the North Bosque River watershed through the calendar year 2022. Monitoring from September 2023 through August 2024 will be sponsored by the TCEQ TMDL program, as well as an upcoming trends report for data through 2023.

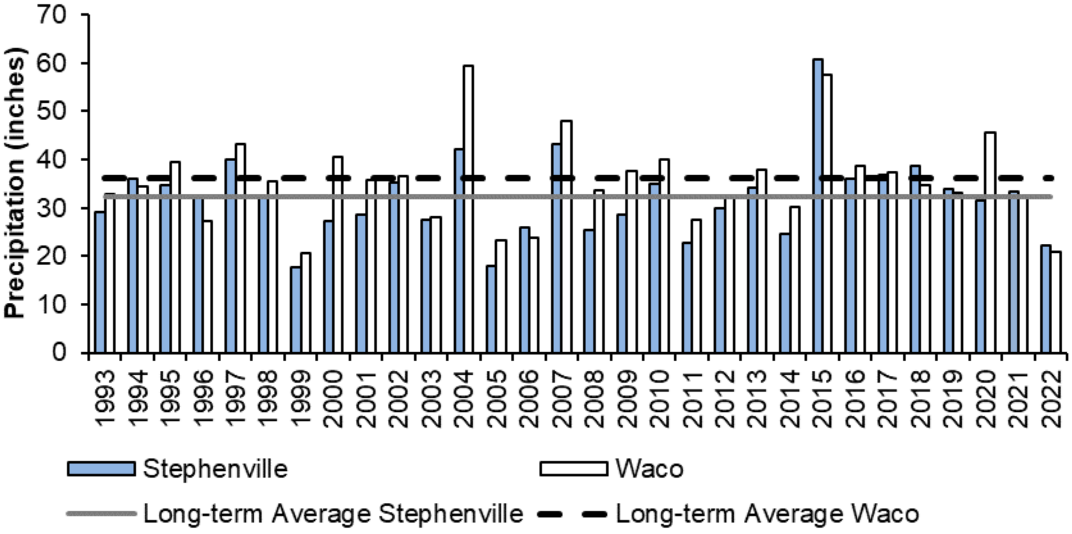

Figure 23 Temporal variability in measured annual precipitation for Stephenville and Waco, Texas

Source: National Oceanic and Atmospheric Administration, National Climatic Data Center.

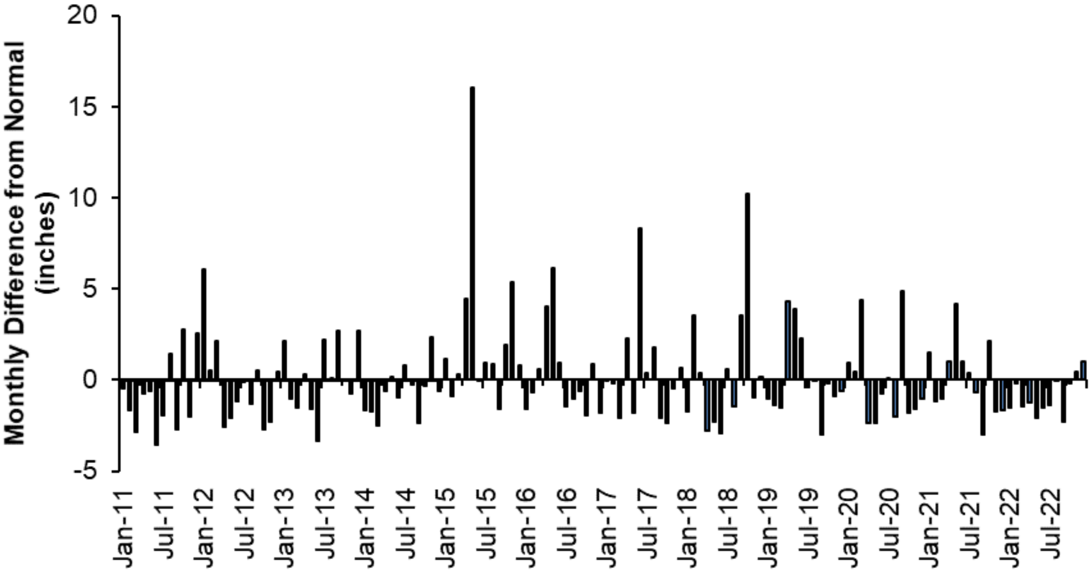

Figure 24 Monthly difference from normal precipitation from January 2011 through December 2022 for Stephenville, Texas

Source: National Oceanic and Atmospheric Administration, National Climatic Data Center.

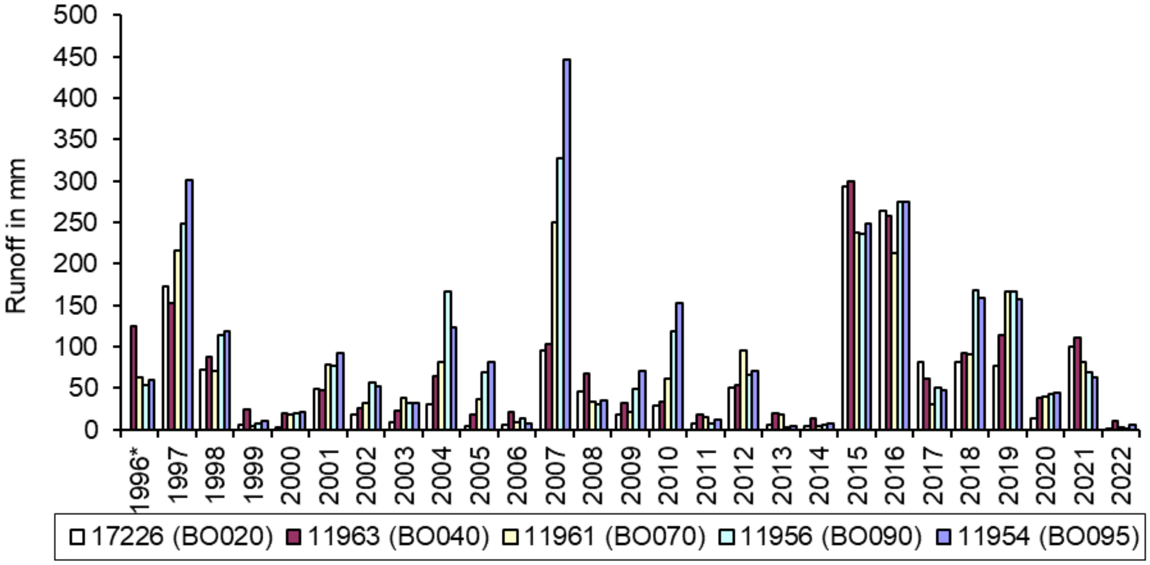

Figure 25 Annual runoff in millimeters for gaged stations along the North Bosque River

Asterisk indicates no data for 17226 (BO020) in 1996. Stations are listed in order of most upstream to most downstream.

References

APHA, American Public Health Association, American Water Works Association, and Water Environment Federation. 1992. Standard methods for the examination of water and wastewater, 18th edition. APHA, Washington, D.C.

Bekele, A. and A. McFarland. 2004. Regression based flow adjustment procedures for trend analysis of water quality data. Transactions of the American Society of Agricultural Engineers 47(4):1093-1104.

Bland, J.M., and D.G. Altman. 1986. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet i:307-310.

BRA, Brazos River Authority. 1995. Quality assurance project plan for the Bosque River watershed pilot project. Brazos River Authority, Waco, Texas.

Buchanan, T.J., and W.P. Somers. 1969. Chapter A8: Discharge measurements at gaging stations. In Techniques of Water-Resources Investigations, Reports Book 3. United States Geological Survey, Arlington, Virginia.

Cleveland, W. S. 1979. Robust locally weighted regression and smoothing scatterplots. Journal of American Statistical Association. 74:829-836.

Dr. Gobbler, 2022. Dr. Gobbler, Everything comes out better in the end! [Online] www.drgobbler.com (link verified July 11, 2023).

Gilbert, R.O. 1987. Statistical methods for environmental pollution monitoring. Van Nostrand. Reinhold, New York.

Gilliom, R.J. and D.R. Helsel. 1986. Estimation of distributional parameters for censored trace level water quality data. 1. Estimation techniques. Water Resources Research 22:135-126.

Helsel, D.R., D.K. Mueller, and J.R. Slack. 2006. Computer program for the Kendall family of trend tests. United States Geological Survey Scientific Investigations Report 2005-5275. USGS, Reston, Virginia.

Helsel, D.R. and R. M. Hirsch, 2002. Statistical methods in water resources techniques. In Water Resources Investigations, Book 4, Chapter A3. United States Geological Survey.

Hirsch, R.M. and J.R, Slack, 1984. A nonparametric trend test for seasonal data with serial dependence. Water Resources Research 20: 727-732.

Houser, J.B., and L.M. Hauck. 2010. Refinement and application of the North Bosque River TMDL modeling system. Prepared for the Texas Commission on Environmental Quality TMDL Team by the Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, PR1001.

Kebreab, E., A.V. Hansen, and A.B. Leytem. 2013. Feed management practices to reduce manure phosphorus excretion in dairy cattle. Advances in Animal Biosciences 4:37-41.

Langland, M. J., R. E. Edwards, and L. C. Darell. 1998. Status yields and trends of nutrients and sediment and methods of analysis for the nontidal data collection programs, Chesapeake Bay Basin, 1985-96. U.S. Department of the Interior, United States Geological Survey. Open-File Report 98-17.

McBride, G. 2000. Anomalies and remedies in non-parametric seasonal trend tests and estimates. Hamilton, New Zealand, National Institute of Water & Atmospheric Research, March 2000.

Millican, J. and T. Adams. 2022. Assessment of water quality trends for the North Bosque River through 2021. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR2206

Millican, J. and T. Adams. 2021. Assessment of water quality trends for the North Bosque River through 2020. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR2108

Millican, J. and T. Adams. 2020. Assessment of water quality trends for the North Bosque River through 2019. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR2002

Millican, J., T. Adams, A. McFarland. 2019. Assessment of water quality trends for the North Bosque River through 2018. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1907.

McFarland, A. and T. Adams. 2018. Assessment of water quality trends for the North Bosque River through 2017. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1804.

McFarland, A. and T. Adams. 2017. Assessment of water quality trends for the North Bosque River through 2016. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1702.

McFarland, A. and T. Adams. 2016. Assessment of water quality trends for the North Bosque River through 2015. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1605.

McFarland, A. and T. Adams. 2015. Assessment of water quality trends for the North Bosque River through 2014. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1506.

McFarland, A. and T. Adams. 2014a. Assessment of water quality trends for the North Bosque River through 2013. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1405.

McFarland, A., and T. Adams. 2014b. Semiannual water quality report for the Bosque River watershed (Monitoring Period: Jan. 1, 2007 – Dec. 31, 2013). Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1404.

McFarland, A. and T. Adams. 2013. Assessment of water quality trends for the North Bosque River through 2012. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1306.

McFarland, A., and T. Adams. 2012. Semiannual water quality report for the Bosque River watershed and Lake Waco (Monitoring Period: Jan. 1, 2005 - Dec.31, 2011). Texas

Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1202.

McFarland, A. and H. Jones. 2006. Chapter 2: Geographic information system layers and associated metadata. In: Sampling history report – Final project report for monitoring to support North Bosque River model refinement. Report to TMDL Team, Texas Commission on Environmental Quality prepared by the Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0613.

McFarland, A. and J. Millican. 2012. Assessment of water quality trends for the North Bosque River through 2011. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1203.

McFarland, A. and J. Millican. 2011. Assessment of water quality trends for the North Bosque River through 2010. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1103.

McFarland, A. and J. Millican. 2010. Assessment of water quality trends for the North Bosque River through 2009. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1002.

McFarland, A. and J. Millican. 2009. Interim annual assessment of water quality trends for the North Bosque River through 2008. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0902.

McFarland, A. and J. Millican. 2008. Interim annual assessment of water quality trends for the North Bosque River through 2007. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0803.

McFarland, A. and J. Millican. 2007. Interim annual assessment of water quality trends for the North Bosque River through 2006. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0703.

McFarland, A. and J. Millican. 2006. Interim annual assessment of water quality trends for the North Bosque River through 2005. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR0612.

Meals, D.W., S.A. Dressing, and T.E. Davenport. 2010 Lag time in water quality response to best management practices: A review. Journal of Environmental Quality 39:85-96.

Miller, R., A. Young, J. Major, and L. Trinca. 2010. Phosphorus in dairy cattle diets. Utah State University Cooperative Extension, AG/Dairy/2010-01pr.

Millican, J., McFarland, A. and T. Adams. 2019. Assessment of water quality trends for the North Bosque River through 2018. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, TR1907.

NCDC, National Climatic Data Center. 2022. Climate data online. National Oceanic and Atmospheric Administration, Washington, D.C. [Online] https://www.ncdc.noaa.gov/cdo-web/ (accessed May 12, 2022 for daily and normal precipitation information; link verified May 31, 2022).

NCDC, National Climatic Data Center. 2014. Historical palmer drought indices. National Oceanic and Atmospheric Administration, Washington, D.C. [Online] https://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/ (link verified May 31, 2022).

Newell, A. D., D. J. Blick, R. C. Hjort. 1993. Testing for trends when there are changes in methods. Water, Air, and Soil Pollution 67:457-468.

Narasimhan, B., X. Zhang, and R. Srinivasan. 2005. Land use/land cover classification of Bosque River watershed using LANDSAT-7 enhanced thematic mapper (ETM+) imagery. Final Report submitted to TIAER by the Spatial Science Laboratory, Texas Agricultural Experiment Station, College Station.

NRC, National Research Council. 2001. Nutrient requirements of dairy cattle, 7th revised edition. National Academy Press, Washington, D.C.

Powell, J.M., and L.D. Satter. 2005. Dietary phosphorus levels for dairy cows. USDA NRCS Bulletin. [Online] https://sera17dotorg.files.wordpress.com/2015/02/bmp_dietary_phosphorus.pdf (link verified May 31, 2022).

Reckhow, K. H., K. Kepford, and W. W. Hicks. 1993. Methods for the analysis of lake water quality trends. United States Environmental Protection Agency, Office of Water, Washington, D.C., EPA 841-R-93-003.

Sansinena, M., L.D. Bunting, S.R. Stokes, and E.R. Jordan. 1999. A survey of trends and rationales for P recommendations among Mid-South nutritionists. p. 51–54. In Proc. Mid-South Ruminant Nutr. Conf., Dallas, TX.

SAS Institute. 2011. The SAS system for windows. Version 9.3. SAS Inst., Cary, NC.

Stein, S.K. 1977. Calculus and analytic geometry. 2nd ed. McGraw-Hill Book Company, New York, N.Y.

TCEQ, Texas Commission on Environmental Quality. 2021. Status report: Implementing TMDLs to reduce phosphorus, improving water quality in the North Bosque River. TCEQ, Austin, Texas (June 2021). [Online] www.tceq.texas.gov/downloads/water-quality/tmdl/north-bosque-river-narrative-criteria-06/06-as-204-fy2021-bosque-river-status-report-final.pdf (link verified July 11, 2023).

TCEQ, Texas Commission on Environmental Quality. 2014. June 13, 2014. [Online] www.tceq.texas.gov/downloads/permitting/wastewater/agriculture/cafo-general/cafo-gp-2019.pdf (link verified July 11, 2023).

TCEQ, Texas Commission on Environmental Quality. 2012. Status report: Implementing TMDLs to reduce phosphorus, improving water quality in the North Bosque River. TCEQ, Austin, Texas (May 2012).

TCEQ, Texas Commission on Environmental Quality. 2012b. Surface water quality monitoring procedures, Volume 1. TCEQ, Monitoring Operations Division, Austin, Texas (RG-415, revised August 2012). [Online] www.tceq.texas.gov/publications/rg/rg-415 (link verified July 11, 2023).

TCEQ, Texas Commission on Environmental Quality. 2011. Status report: Implementing TMDLs to reduce phosphorus, improving water quality in the North Bosque River. TCEQ, Austin, Texas (April 2011).

TCEQ, Texas Commission on Environmental Quality. 2009. Water quality in the North and Upper North Bosque Rivers February 2009: Status report of activities to address elevated nutrient concentrations. TCEQ, Austin, Texas (March 3, 2009).

TCEQ, Texas Commission on Environmental Quality. 2008. Surface water quality monitoring procedures, Volume 1. TCEQ, Monitoring Operations Division, Austin, Texas (RG-415).

TCEQ, Texas Commission on Environmental Quality. 2003. Surface water quality monitoring procedures, Volume 1. TCEQ, Monitoring Operations Division, Austin, Texas (RG-415).

TCEQ, Texas Commission on Environmental Quality, and TSSWCB, Texas State Soil and Water Conservation Board. 2002. An implementation plan for soluble reactive phosphorus in the North Bosque River watershed for segments 1226 and 1255. TCEQ Strategic Assessment Division and TSSWCB TMDL Teams, Austin, Texas (approved by TCEQ Dec. 13, 2002).

Texas Demographic Center. 2020. Estimates of the Total Populations of Counties and Places in Texas, November 2020. [Online] https://demographics.texas.gov/Resources/TPEPP/Estimates/2019/2019_txpopest_place.pdf (accessed May 17, 2022).

Texas State Data Center. 2015. Descriptive Tables – Population in 1990 and 2000, numerical and percent change in population from 1990 to 2000 in places in Texas. [Online] https://demographics.texas.gov/Data/Subject/Population (accessed July 10, 2015; link verified July 11, 2023).

TIAER, Texas Institute for Applied Environmental Research. 2017. Evaluating effectiveness of total maximum daily load (TMDL) implementation plan (I-Plan) Activities within the North Bosque River watershed quality assurance project plan for monitoring, Rev. 0. Prepared in cooperation with the TCEQ Total Maximum Daily Load Program by TIAER, Tarleton State University, Stephenville, Texas.

TIAER, Texas Institute for Applied Environmental Research. 2016. Evaluating effectiveness of total maximum daily load (TMDL) implementation plan (I-Plan) activities within the North Bosque River watershed quality assurance project plan, Rev. 0. Prepared in cooperation with TCEQ and USEPA Nonpoint Source Program CWA 319(h) by TIAER, Tarleton State University, Stephenville, Texas.

TIAER, Texas Institute for Applied Environmental Research. 2013. Evaluating effectiveness of implementation activities within the North Bosque River watershed quality assurance project plan, Rev. 2. Prepared in cooperation with the TCEQ and USEPA Nonpoint Source Program CWA 319(h) by TIAER, Tarleton State University, Stephenville, Texas.

TIAER, Texas Institute for Applied Environmental Research. 2010a. North Bosque River watershed water quality assessment Clean Water Act Section 319(h) quality assurance project plan, rev. 4. Prepared in cooperation with TCEQ and USEPA by TIAER, Tarleton State University, Stephenville, Texas.

TIAER, Texas Institute for Applied Environmental Research. 2010b. North Bosque River watershed water quality assessment surface water quality monitoring program quality assurance project plan, rev. 0. Prepared in cooperation with TCEQ by TIAER, Tarleton State University, Stephenville, Texas.

TIAER, Texas Institute for Applied Environmental Research. 2005. United States Department of Agriculture Bosque River initiative quality assurance project plan, Rev. 5. Prepared in cooperation with TCEQ by TIAER, Tarleton State University, Stephenville, Texas.

TIAER, Texas Institute for Applied Environmental Research. 1993. Quality assurance project plan for the National Pilot Project. TIAER, Tarleton State University, Stephenville, Texas.

TNRCC, Texas Natural Resource Conservation Commission. 2001. Two total maximum daily loads for phosphorus in the North Bosque River for Segments 1226 and 1255. Strategic Assessment Division, TMDL Team, TNRCC, Austin, Texas (adopted February 2001; approved by EPA December 2001).

Tukey, J. W., 1977. Exploratory data analysis. Addison-Wesley Publishing.

USDA-NASS, United States Department of Agriculture National Agricultural Statistics Service. 2023. Milk: production per cow by year, US, charts and maps. USDA-NASS (02-23-2023) [Online] https://www.nass.usda.gov/Charts_and_Maps/Milk_Production_and_Milk_Cows/cowrates.php (link verified July 11, 2023).

USEPA, United States Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. Environmental Monitoring and Support Laboratory, Office of Research and Development, USEPA, Cincinnati, Ohio. EPA-600/4-79-020, Revised March 1983.

USGS, United States Geological Survey. National land cover database 2016 (NLCD 2019) Product Data Downloads [Online] www.mrlc.gov/data?f%5B0%5D=category%3Aland%20cover&f%5B1%5D=year%3A2011 (verified July 11, 2023)

Ward, R.C., J.C. Loftis, H.P. DeLong, and H.F. Bell. 1988. Groundwater quality: A data analysis protocol. Journal of the Water Pollution Control Federation 60:1938-1945.

Appendix A. Storm Conditions 2008-2021

2008 and 2009

In 2008 and 2009, because of judicious efforts on the part of the field crew and favorable weather conditions, TIAER was able to monitor most storms, while missing only a few relatively small events in 2009. In late November 2009, there was one event that caused a small rise in water level at most stations but led to a moderately sized runoff event at stations 11961 (BO070) and 13486 (GC100), during which storm samples were not collected. A routine grab sample collected during this November 2009 event was used to represent the storm water quality for this event.

2010

During most of 2010, storm sampling was restricted due to funding limits. Flow meters were kept operational and routine biweekly grab sampling continued, but only limited storm monitoring occurred. From January through May 2010, storm samples were collected only at stations 11961 (BO070) and 11954 (BO095). From May through September 2010, no storm monitoring occurred at any of the seven stations. Starting in September 2010, new funding was obtained allowing storm sampling to be reinitiated at all seven storm stations. Between September and December 2010, all events with a rise in water level of over 0.5 ft were monitored.

Although several storms during 2010 were not directly monitored, the contribution of these storms to nonpoint storms loadings was still important in evaluating annual trends. Because changes in water quality associated with nonpoint source contribution often occur gradually, data from storms evaluated in 2009 and 2010 for most stations were used to estimate storm loadings. Of note for station 13486 (GC100), storm data from 2008 were included due to the paucity of storms that occurred at this station in 2009. Details on how previous storm concentrations were associated with 2010 storms are presented in McFarland and Millican (2011).

2011

In 2011, most months had relatively little rainfall and extreme drought conditions occurred across the watershed by late summer, enabling all storms that occurred to be monitored. Dry conditions decreased the number of routine grab samples collected, particularly during the summer and fall months at sites 17226 (BO020), 11961 (BO070), 18003 (BO083), 11826 (NC060), and 12486 (GC100) (see McFarland and Adams, 2012). The driest location was 12486 (GC100), where only one routine grab sample was collected in 2011. This limited data set, thus, precluded trend analysis for station 12486 (GC100) for data through 2011. At stations 17226 (BO020), 11961 (BO070), 18003 (BO083), and 11826 (NC060), stream water was not flowing 31 to 53 percent of the time during biweekly sampling (McFarland and Adams, 2012).

2012

In 2012, stream conditions were still often low, but routine grab samples were generally collected more frequently than in 2011. The only exception was station 17226 (BO020), which had fewer grab samples in 2012 (15 in 2011 and 12 in 2012). Routine grab samples were collected during all biweekly monitoring events at stations 11963 (BO040), 11961 (BO070), 11956 (BO090), and 11954 (BO095). At the other four stations, water was not flowing 42 to 54 percent of the time when visited for biweekly sampling. Most storms in 2012 occurred between January and early June, with a single fall event in late September. All notable elevated flows were monitored in 2012, except an event that occurred over the Christmas holidays (starting Dec. 25) at stations 17726 (BO020), 11963 (BO040), and 11961 (BO070). For annual loading calculations, EMCs from the September storm event were associated with this December rise in water level.

2013

In 2013, stream conditions were also quite low, with moderate drought conditions noted for most of the year based on historical Palmer Drought Indices (NCDC, 2014). While pooled or no-flow conditions are not unusual along portions of the North Bosque River, particularly in the summer months at stations 17726 (BO020), 11961 (BO070), and 18003 (BO083), they are unusual for the most downstream stations 11956 (BO090) and 11954 (BO095). At station 13486 (GC100) on Green Creek, flowing waters occurred only in the month of April in 2013. In August and part of September 2013, pooled conditions were noted at 11956 (BO090) and 11954 (BO095) during biweekly routine monitoring (see McFarland and Adams, 2014b). Pooled conditions were also noted at 11956 (BO090) in early July 2013. Some storms did occur in the fall, and in October 2013, the auxiliary pump at station 11956 (BO090) had to be pulled and sent in for repairs. The auxiliary pump aids in pulling storm samples up the steep bank at this location, which has a height of over 20 feet. Only one relatively small storm occurred in November 2013 while the auxiliary pump was out, during which a storm grab was collected at station 11956 (BO090).

Compared to 2012, storms were much smaller in volume, but more frequent and more evenly spaced throughout 2013. All storms with a notable rise in water level (generally 0.25 ft or greater) were monitored except two storms in December 2013. On Dec. 8-9, 2013, an ice storm led to a notable rise in water level at most stations, but also caused unsafe driving conditions for sample retrieval. Another notable rise in stream water level occurred in response to rainfall runoff on Dec. 21, 2013. Due to a planned power outage associated with construction work on the Tarleton State University campus that affected the TIAER laboratory and, thus, the ability of the lab to process samples, samplers were not activated during the Dec. 21, 2013 storm event. Loadings for these December events were based on EMCs of similar size events collected during 2013 at each station.

2014

In 2014, moderate drought conditions were indicated for much of the year (NCDC, 2014), with no storms occurring in January, February, or March. In April 2014, storm samples were collected only at station 17226 (BO020) in association with a small, isolated thunderstorm just north of Stephenville. In May and June 2014, there were rainfall events leading to storm samples throughout the watershed, while rains were such during the rest of the year that elevated flows were monitored almost exclusively in the upper third of the watershed. Because there were so few events in 2014, all elevated flow events, except a relatively small event occurring between Dec. 23-25, were monitored, except at station 13486 (GC100) due to bridge work at this location.

Between January and March 2014, Green Creek was dry, and on March 12, 2014, the storm sampler and flow meter at station 13486 (GC100) were removed for renovation of the county road bridge. Work on the bridge was completed in late September 2014, and the sampler and flow meter were reinstalled. While sampling equipment was removed, station 13486 (GC100) was still visited biweekly, and during all 26 biweekly monitoring events in 2014, station 13486 was pooled with no flow or dry, so no grab samples were collected. One storm event in May and one in June 2014 likely led to elevated flows at Green Creek station, but because the flow meter as well as the sampler were removed, these storms were not monitored. The bridge renovation work caused substantial changes in the cross-section of the creek at station 13486 (GC100). A new rating curve was developed based on stage-discharge measurements collected post-September 2014. While this new stage-discharge was being developed, a provisional rating curve was used based on standard hydraulic relationships of stage to the cross-sectional area for flow-weighting of storm samples.

During most of 2014, storms grabs continued to be collected at station 11956 (BO090), with elevated flows. The auxiliary pump that was found to be inoperable in October 2013 was finally repaired, returned to TIAER, and reinstalled Aug. 7, 2014.

2015

In 2015, only a few storms occurred between January and March 2015, but a series of rain events starting in mid-April and continuing through May led to elevated flows and flooding throughout the watershed. In April 2015, 7.3 inches of precipitation fell in Stephenville and in May 2015, 20.5 inches. Normal monthly precipitation is 2.5 inches for April and 4.4 inches for May (NCDC, 2022). These elevated flows in April and May were largely monitored, though large debris carried by these storms damaged sampling equipment at 11954 (BO095) in late April and 11956 (BO090) and 11961 (BO070) in late May. Flow meters and samplers were removed from shelters at 11954 (BO095) and 11956 (BO090) due to concerns with anticipated flooding on May 29, 2015. These three sampling stations are collocated with USGS stations, so USGS data were paired with daily storm grabs data until repairs could be made.

The large number of repairs needed from the May events and limited project funding precluded storm monitoring of an event in mid-June. Loadings for this June event were estimated based on water quality measured during a similar sized event in late July. Storm grabs were collected at an event in early July at all stations, as it was unanticipated and equipment repairs had not yet occurred. In late July, all three sampling stations (11961 [BO070], 11956 [BO090], and 11954 [BO095]) damaged during the April and May events were repaired and operational.

Unfortunately, heavy rains in the lower two-thirds of the watershed in late October 2015 again caused damage at station 11954 (BO095), at which repairs could not be safely conducted until February 2016. Storms for October through December 2015 at station 11954 (BO095) were represented by daily storm grabs. Also, in November 2015, an unanticipated rainfall of about four inches occurring Nov. 27–28, 2016, led to a relatively large event over the Thanksgiving weekend. Due to the unavailability of staff over the holiday weekend, this storm was not monitored in its entirety, but because stream levels were still elevated on Nov. 30 when staff returned to work, storm grabs were collected as representative of this event.

2016

In 2016, storm monitoring was quite limited due to funding limitations. Storm sampling occurred January through March and then was limited to an event in November. Storms occurring April through October were not monitored, as well as a small event in December.

Between January and March 2016, there were some issues with storm monitoring. At station 11954 (BO095), daily storm grabs were collected with elevated flows through January 2016, because large debris associated with elevated flows in October 2015 damaged the sampler line. On Feb. 11, 2016, stream levels dropped sufficiently that the field crew was able to fix the intake lines at station 11954 for the automated sampler. While storm monitoring station 11954 (BO095) had been fixed and operational for storm monitoring in late February, in March 2016, elevated flows once again led to debris (a large tree) wiping out much of the intake line, leading again to the collection of daily storm grabs until repaired in July.

Highly elevated flows occurred at most stations in mid-April in response to about 6 to 10 inches of rain over several days, and again the later part of May in response to 4 to 10 inches of rain occurring on very saturated ground. Between mid-April and late May, smaller rain events led to smaller pulses of flow. This kept the ground very moist, causing flooding in the upper third of the watershed in late May.

Flooding in late May into early June submerged storm monitoring stations 17226 (BO020) and 11963 (BO040), causing severe damage. With receding high water-levels, the disconnection of sampler and flow meter lines was apparent at station 11956

(BO090). Repairs to stations 17226 (BO020) and 11963 (BO040) were completed on June 30, 2016 and flows during the period when these stations were inoperable were estimated using stage data from station 11961 (BO070) and 13486 (GC100). As of July 28, 2016, stations 11954 (BO095) and 11956 (BO090) were again operational.

Unfortunately, debris once again took out intake lines at station 11954 (BO095), with elevated flows in mid-August. The North Bosque rose about 15 feet overnight at 11954 (BO095) on Aug. 18 in response to about six inches of rain occurring largely in the lower half of the watershed. The tubing was reinstalled at station 11954 on Aug. 31, with assistance provided by one of the Bosque County Commissioners in removing a large tree that was lodged between the bridge and the sampling station. For stations 11954 (BO095) and 11956 (BO090), the USGS gaging stations were still operational during these periods when the TIAER automated stations were inoperable.

While heavy rains led to flood waters throughout the watershed in late May and early June, relatively little rain occurred in June or July. In mid-August, about two to six inches of rain occurred Aug. 17-20, 2016, with the heaviest rainfall in the most southern portion of the watershed. While some small events occurred in September and October, the next large event occurred in November 2016, with storm samples collected at all stations. Again, in December 2016, only small rises in streamflow occurred, which were not directly monitored as storms.

To calculate monthly loading for 2016, concentrations of time-related, biweekly grab samples were used to represent elevated flow periods not monitored, as they often corresponded by happenstance with periods of elevated flow.

2017

In 2017, storm monitoring was limited to three or four events at each station. Based on relationships developed for 2010 events (McFarland and Millican, 2011), a log-linear relationship between average storm flow and the EMC of the few events monitored in 2017 was used to estimate the concentration; thus, loadings associated with storms that were not monitored in 2017. This approach seemed appropriate given the storms that were monitored represented small to large events for the year. Events monitored were in January, April, June, and November 2017, although in November 2017, insufficient runoff occurred at stations 11954 (BO095) and 11826 (NC060) to enable storm monitoring. Precipitation in Stephenville within the headwaters of the North Bosque River totaled 36.8 inches for 2017, well above the long-term average of 31.5 inches. The heaviest rainfall occurred in June, with a total of 12 inches or about one-third of the total rainfall for the year. Flow conditions for each of the seven stations for 2017 indicated a pulsing of storms throughout the year, but a general decline in flow from July through December.

2018

In 2018, five storms were monitored at BO090 and BO095 and six were monitored at BO020, BO040, and BO070 along the mainstem of the North Bosque River. Only two storms were monitored at tributary station 13486 (GC100) due to low or no flow conditions that persisted through much of the year at this location. Sampling was discontinued at tributary station 11826 (NC060) at the end of August 2018, which resulted in only two storms being monitored in 2018 at this location. Precipitation in Stephenville within the headwaters of the North Bosque River totaled 38.8 inches for 2018, well above the long-term average of 31.5 inches. The heaviest rainfall occurred in October, with a total of 13.4 inches. Low flow or drought conditions affected the watershed for most of 2018, with some small storms occurring. In October 2018, heavy rainfall events led to elevated flows throughout the watershed.

2019

In 2019, only one storm event was monitored. The storm event was sampled for five days starting on April 24 through April 28, 2019 at all six storm monitoring locations. Storm sampling that occurred during September and October of 2018 resulted in budget limitations for storm sampling to occur during the May through August FY19 period. Compounding the issue, relatively dry conditions were present for much of the period of September through December of 2019.

2020

In 2020, storm monitoring was disrupted due to travel restrictions associated with the COVID-19 pandemic. However, storms were monitored during March and July. Two storms were monitored at stations 17226 (BO020), 11963 (BO040), 11956 (BO090), and 11954 (BO095). Three storms were monitored at station 11961 (BO070), and only one storm event was monitored at tributary station 13486 (GC100).

Precipitation in Stephenville within the headwaters of the North Bosque River totaled 31.4 inches for 2020, slightly below the long-term average of 33.2 inches. The heaviest rainfall occurred in March, with a total of 7.3 inches. Low flow conditions affected the watershed for most of 2020.

2021

In 2021, storms were monitored during March, April, and May. Four storms were monitored at stations 17226 (BO020), 11963 (BO040), 13486 (GC100) 11956 (BO090), and 11954 (BO095). Three storms were monitored at station 11961 (BO070).

Precipitation in Stephenville within the headwaters of the North Bosque River totaled 33.2 inches for 2021, slightly above the long-term average of 32.6 inches. The heaviest rainfall occurred in May, with a total of 8.7 inches.

Appendix B. Annual Box-and-Whisker Plots for Bacteria

The following box-and-whisker plots are of flow-adjusted bacteria concentrations from routine grab data collected at stations within the North Bosque River watershed. The timeframe of these plots varies by station depending on available flow and bacteria data, but generally represents the mid-1990s through 2022. These plots correlate with trend results presented in Tables 7–11 and 13 within the body of this report. General findings are that bacteria concentrations are significantly decreasing at most routine monitoring locations within the North Bosque River watershed.

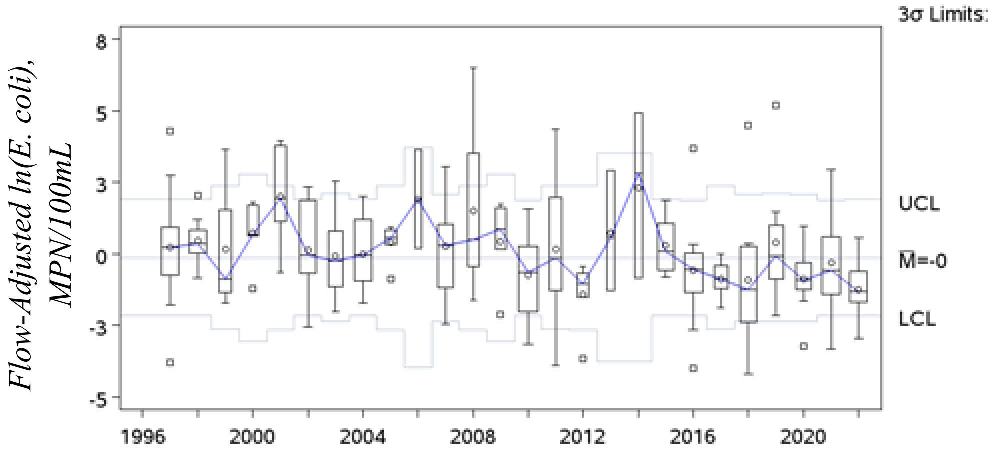

Figure B-1 Annual box-and-whisker plots of residuals from monthly flow-weighted and flow-adjusted *E. coli* data for station 17226 (BO020)

Station 17726 (BO020) is located on the North Bosque River at Farm-to-Market 8 immediately northeast of Stephenville.

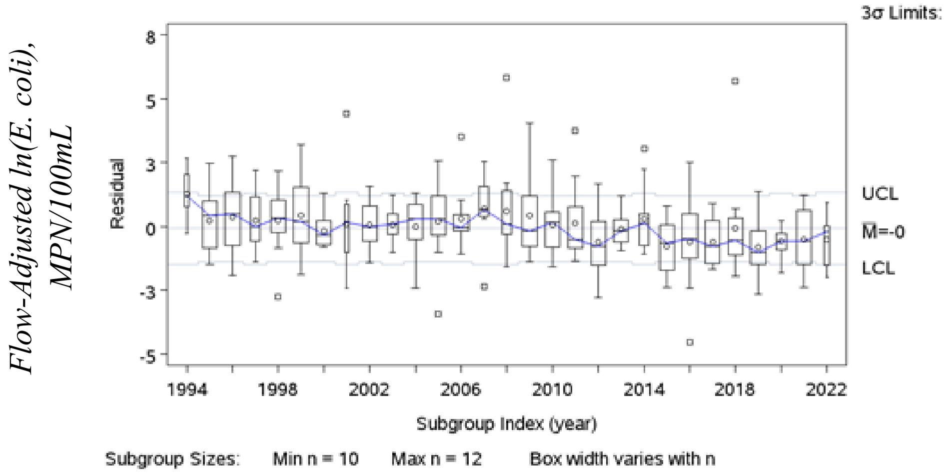

Figure B-2 Annual box-and-whisker plots of monthly flow-weighted and flow-adjusted *E. coli* data for station 11963 (BO040)

Station 11963 (BO040) is located at Erath County Road 454 in Stephenville.

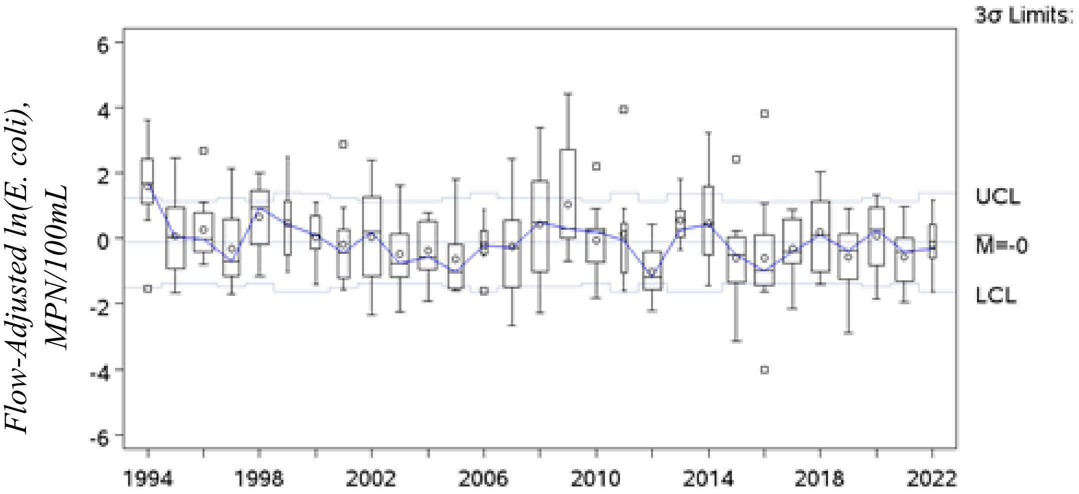

Figure B-3 Annual box-and-whisker plots of monthly flow-weighted and flow-adjusted *E. coli* data for station 11961 (BO070)

Station 11961 is located at Walnut Street/US 281 near Hico.

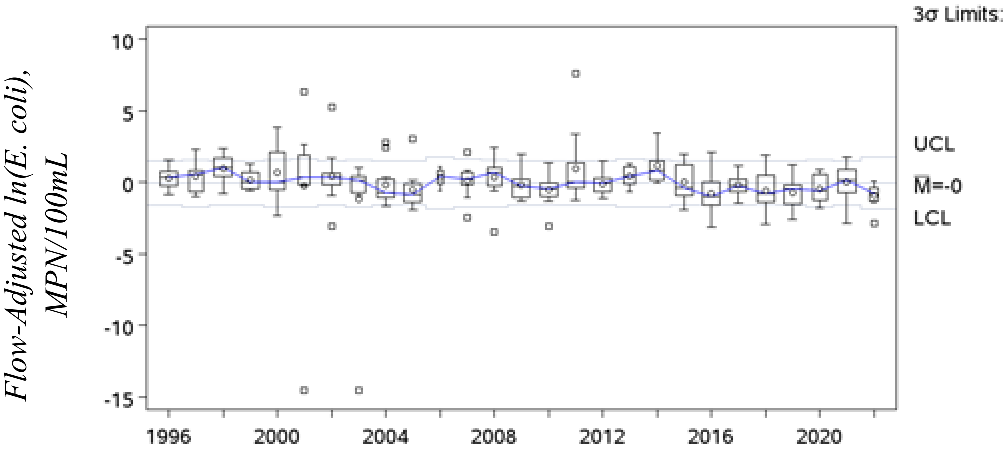

Figure B-4 Annual box-and-whisker plots of monthly flow-weighted and flow-adjusted *E. coli* data for station 11956 (BO090)

Station 11956 (BO090) is located at Farm-to-Market 219 northeast of Clifton.

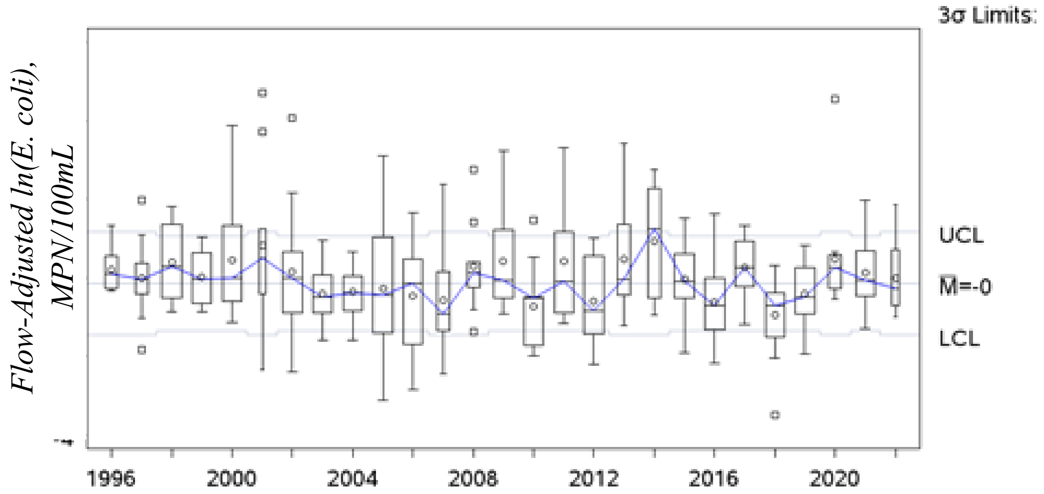

Figure B-5 Annual box-and-whisker plots of monthly flow-weighted and flow-adjusted *E. coli* data for station 11954 (BO095)

Station 11954 (BO095) is located immediately upstream of River Road near SH 6 west of Valley Mills.