Prepared in cooperation with Missouri Department of Natural Resources

Use of Continuous Water-Quality Time-Series Data to Compute Total Phosphorus Concentrations and Loads for the Missouri River at St. Joseph and Hermann, Missouri, 2007–22

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U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph showing hydrologic technician accessing real-time water-quality equipment for maintenance, Missouri River at St. Joseph, Missouri, on May 18, 2023, by U.S. Geological Survey.

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By Kendra M. Markland

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mga/d)	3,785	cubic meter per day (m^3/d)
	Mass	
ton, short (2,000 lb)	0.9072	metric ton (t)
	Yield	
pound per square mile per year ($lb/mi^2/yr$)	0.1751	kilogram per square kilometer per year ($kg/km^2/yr$)
pound per square mile per day ($lb/mi^2/d$)	0.1751	kilogram per square kilometer per day ($kg/km^2/d$)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Datums

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

A water year is the period from October 1 to September 30 and is designated by the year in which it ends; for example, water year 2022 was from October 1, 2021, to September 30, 2022.

Abbreviations

AIC	Akaike information criterion
BCF	bias correction factor
FNU	formazin nephelometric unit
LOADEST	LOAD ESTimator
log	logarithm
NLRS	Nutrient Loss Reduction Strategy
NWIS	National Water Information System
NWQN	National Water Quality Network
R^2_a	adjusted coefficient of determination
RMSE	root mean square error
SPARROW	SPAtially Referenced Regressions on Watershed attributes
USGS	U.S. Geological Survey
WRTDS	weighted regression on time, discharge, and season
YSI	Yellow Spring Instruments

Use of Continuous Water-Quality Time-Series Data to Compute Total Phosphorus Concentrations and Loads for the Missouri River at St. Joseph and Hermann, Missouri, 2007–22

By Kendra M. Markland

Abstract

In support of Missouri's Nutrient Loss Reduction Strategy, which was created to reduce the nutrient contamination of Missouri's waterways from point and nonpoint sources, total phosphorus concentrations and loads were computed for the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500) for October 2007 to September 2022 using surrogate models and continuous turbidity sensor data. To obtain a more complete total phosphorus record for the study period, LOAD ESTimator (LOADEST) regression models using flow were used when turbidity sensor data were unavailable to estimate daily total phosphorus loads. This report presents the methods and results for the computed total phosphorus concentrations, loads, and yields for the two study sites on the Missouri River. With continued data collection and ongoing model evaluation and maintenance, the surrogate models may be useful into the future for computing total phosphorus concentrations and loads.

Daily mean total phosphorus concentrations calculated using a surrogate model at the Missouri River at St. Joseph, Mo., streamgage during the 15-year study period (water years 2008 through 2022) ranged from 0.104 to 4.56 milligrams per liter (mg/L; median of 0.272 mg/L), and computed total phosphorus daily loads (with gaps in the daily record filled using the LOADEST regression model) ranged from 5.19 to 1,760 tons per day (tons/d; median of 36.5 tons/d). Annual loads ranged from 9,570 tons in water year 2022 to 50,500 tons in water year 2019. The total load for the study period was 437,000 tons.

For the Missouri River at Hermann, Mo., streamgage during the same 15-year study period, daily mean total phosphorus concentrations, calculated using surrogate models applied to low and high turbidity values, ranged from 0.183 to 1.97 mg/L (median of 0.319 mg/L), and computed total phosphorus daily loads (with gaps in the daily record filled using the LOADEST regression model) ranged from 12.7 to 1,970 tons/d (median of 76.8 tons/d). Annual loads ranged from 22,600 tons in water year 2022 to 101,000 tons in water year 2019. The total load for the study period was 833,000 tons, which is nearly twice that at the Missouri River at St. Joseph, Mo., streamgage.

Introduction

The U.S. Geological Survey (USGS) and the Missouri Department of Natural Resources collaborated to study total phosphorus concentrations and loads in the Missouri River at St. Joseph, Missouri, streamgage (USGS site number 06818000; hereinafter referred to as the "St. Joseph study site"), and the Missouri River at Hermann, Mo., streamgage (USGS site number 06934500; hereinafter referred to as the "Hermann study site"; fig. 1). The Missouri River is 2,341 miles long, making it the longest river in North America, and drains more than 500,000 square miles (Missouri Department of Conservation, 2023). The Missouri River drains 426,500 square miles at the St. Joseph study site, which is about 82 percent of the drainage area of the downstream Hermann study site (522,500 square miles; table 1; U.S. Geological Survey, 2023).

Like many Midwestern States, Missouri has developed nutrient loss reduction strategies. The Missouri Nutrient Loss Reduction Strategy (NLRS) calls for reductions in nutrient inputs to Missouri's waterbodies and ultimately the Gulf of Mexico (Missouri Department of Natural Resources, 2020). The Missouri NLRS aims to reduce the nutrient contamination of Missouri's waterways from point and nonpoint sources (Missouri Department of Natural Resources, 2020) and has a stated goal to reduce total nitrogen and total phosphorus 20 percent by 2025 and 45 percent by 2035. In an effort to control total phosphorus contamination from point sources, the Missouri Department of Natural Resources imposed a new rule for major wastewater treatment plants in 2023. The new total phosphorus limit of 1 milligram per

Figure 1. Study sites and location of the Missouri River Basin.

Table 1. Location information for the study sites at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

[Data are from the U.S. Geological Survey National Water Information System database (U.S. Geological Survey, 2023). Coordinates are given in decimal degrees. USGS, U.S. Geological Survey; mi^2, square mile]

USGS site number (fig. 1)	Station name	Latitude	Longitude	Drainage area (mi^2)	County	Period of record used in this study
06818000	Missouri River at St. Joseph, Missouri	39.75325	−94.8568333	426,500	Buchanan County	October 2007–September 2022
06934500	Missouri River at Hermann, Missouri	38.70980556	−91.4385	522,500	Montgomery County	October 2007–September 2022

liter (mg/L) as an annual mean was based on design flow applied to municipalities with wastewater treatment plant outflows greater than 1 million gallons per day, as well as major industrial facilities (Missouri Department of Natural Resources, 2023). Wastewater treatment plants can also meet the new requirement through a 75-percent overall reduction in influent to effluent or effluent to effluent of total phosphorus. Despite these regulatory changes to point sources, targeting reductions of nonpoint nitrogen and phosphorus contributions remains a challenge because of widespread potential nutrient sources on the landscape and the variable nature of the inputs dependent on the season and moisture conditions.

The Missouri Department of Natural Resources expends considerable resources on the water-quality monitoring of streams throughout the State. Advances in technology have resulted in the ability to directly measure some nutrients, such as nitrate, in real time using direct-read sensors. However, technology for directly analyzing total phosphorus concentrations in real time has not advanced as quickly. Total phosphorus technologies are more difficult to automate because they require a digestion step, which is challenging to implement in a field setting (Peake, 2022).

Comparisons of continuous nitrate sensor data to discrete nutrient samples indicate that fixed frequency discrete sampling can often miss short-term peaks in nutrient concentrations (Warner and others, 2013). Collection of discrete samples does not represent the variability in total phosphorus patterns in rivers and streams (Jones and others, 2011), as indicated by continuous sensor measurements. The St. Joseph and Hermann study sites have continuous nitrate sensors installed, which enables continuous monitoring of nitrate concentrations and more accurate calculations of nitrogen loads and changes over time. However, without real-time total phosphorus information, a large component of nutrient transport is missing. Because of the difficulty in monitoring phosphorus concentrations in real time, surrogate relations with turbidity, which are specific to each site, are often used to estimate total phosphorus concentrations. The use of the surrogate relation between turbidity and total phosphorus is well established (Jones and others, 2011; Schenk and others, 2016; Garrett, 2019, 2021a, 2021b), with a strong physical relation between total phosphorus loads and sediment-bound phosphorus (Garrett, 2012, 2019). The relation between total phosphorus and streamflow also has been used to supplement concentration and load estimates when turbidity data are missing (Robertson and others, 2018).

To estimate total phosphorus concentrations and loads at the St. Joseph and Herman study sites, turbidity-surrogate models were developed for each site. Because turbidity is dependent on the source of the suspended sediment, surrogate models are site-specific (Grayson and others, 1996; Christensen and others, 2002). When turbidity data were unavailable, streamflow data and the LOAD ESTimator (LOADEST) models were used to estimate daily loads of total phosphorus, and these estimates were used to fill the gaps in the record (Runkel and others, 2004). The complete daily total phosphorus record was used to calculate annual loads and yields of total phosphorus for the study period (water years 2008 through 2022; a water year is the period from October 1 to September 30 and is designated by the year in which it ends). With ongoing model evaluation and maintenance, the turbidity-surrogate models may be useful into the future for total phosphorus concentration and load estimations.

The purpose of this report is to describe the surrogate regression models developed to compute total phosphorus concentrations and loads at the St. Joseph and Hermann study sites for the period starting in October 2007. Continuous sensor data (15-minute interval) and sample results for the study period (water year 2008 through water year 2022) are summarized. The report also describes the use of streamflow data and LOADEST models to estimate daily total phosphorus loads when turbidity data are unavailable. The report summarizes the resulting concentrations, loads, and yields for the two study sites.

Methods

Both the St. Joseph and Hermann sites have streamgages and continuous water-quality stations that transmit measurements made every 15 minutes. Water-quality sensor data, including dissolved oxygen, specific conductance, temperature, and turbidity, are available at both study sites beginning in October 2007. Fluorescent dissolved organic matter data are also currently available at the Hermann study site. Continuous nitrate data are available, beginning in 2021 for the St. Joseph study site, and beginning in 2015 for the Hermann study site. Discrete water samples collected during water years 2008 through 2022 (October 1, 2007, through September 30, 2022) were used for calibration of the turbidity-based surrogate regression models to compute total phosphorus concentrations and loads. When less than 48 percent of the continuous total phosphorus load for the day (owing to missing turbidity data) was available or when turbidity values were outside of the specified range of the surrogate models, streamflow data were used with the LOADEST regression models to estimate daily total phosphorus loads for a more complete load record (Runkel and others, 2004).

Continuous Water-Quality Data Collection

A Yellow Springs Instruments (YSI) EXO turbidity sensor, installed on a YSI EXO multiparameter water-quality sonde, was used to monitor turbidity in formazin nephelometric units at both study sites. The sondes were deployed within a protective polyvinyl chloride pipe with holes cut in it to allow for water flow around the sensors. The sonde at the St. Joseph study site is deployed on the left bank at the downstream abutment of the St. Joseph and Grand Island Railroad Bridge in St. Joseph, Missouri (not shown). The associated gage house that contains the signal transmission equipment is mounted on the bridge railing. The sonde at the Hermann study site is deployed along the bridge pier located on the State Highway 19 bridge at Hermann, Mo. (not shown), and the associated gage house containing the signal transmission equipment is located on the downstream side of the bridge. During some years, sonde deployments were seasonal owing to low water and ice conditions. Data were recorded every 15 minutes and transmitted hourly by way of satellite telemetry. Maintenance and calibration of water-quality sensors followed methods described in Wagner and others (2006). The turbidity sensor was calibrated using a three-point calibration and YSI's calibration standards. The sonde was serviced approximately every 6 to 8 weeks, which included cleaning of the sonde and calibration checks. Missing periods of record are due to equipment failures, biofouling, and (or) data corrections that exceeded correction criteria (Wagner and others, 2006). All continuous turbidity data are available in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2023).

Water Sample Collection and Analysis

Discrete water-quality samples were collected as part of a long-term routine monitoring at both sites funded by the USGS and Missouri Department of Natural Resources. The St. Joseph study site is part of the Missouri Department of Natural Resources and USGS cooperative Ambient Water-Quality Monitoring Network, which is a network of river and stream sites across Missouri that are monitored to assess water resources in Missouri (Markland, 2023). The Hermann study site is part of the USGS National Water Quality Network (NWQN), which is a network of 110 sampling sites established to monitor current water-quality conditions and trends in rivers and streams across the Nation and over time (Riskin and Lee, 2021). Since October 2007, an average of 12 samples per year were collected at the St. Joseph study site and 13 samples per year were collected at the Hermann study site. Sampling was completed according to procedures described by the "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). Samples were analyzed for total phosphorus and other constituents by the USGS National Water Quality Laboratory. All discrete sample data are available in NWIS (U.S. Geological Survey, 2023).

Surrogate Model Development

Surrogate models used simple ordinary least squares regression to relate total phosphorus concentrations in discrete samples to continuous turbidity data. Model development was completed using the statistical software R (R Core Team, 2024) in RStudio software (R version 4.1.3; RStudio Team, 2024). The calibration datasets included discrete total phosphorus concentration matched to the nearest continuous turbidity value. For each study site, a surrogate model for the logarithm (log)-transformed total phosphorous concentration was fitted to the log-transformed turbidity because log-transformation resulted in a better fit of the data. The model form was selected by comparing the Akaike information criterion (AIC) of several potential models (Helsel and others, 2020).

Model residuals were investigated for potential outliers exhibiting undue influence on the models. Plots were evaluated for low residual variance, normality and homoscedasticity of residuals, and a ratio of mean observed (sampled) concentration to computed (simulated) concentration near 1.0. The log-transformed total phosphorus values were retransformed back to the original units to allow for direct calculation of total phosphorus concentrations from continuous turbidity values. Because of the potential bias introduced to the calculated total phosphorus concentration by retransformation, a nonparametric smearing bias-correction factor was applied (Duan, 1983). To compute total phosphorus loads in U.S. short tons per day, the continuous computed total phosphorus concentrations (in milligrams per liter) are multiplied by continuous streamflow (in cubic feet per second) and a unit conversion factor. The daily loads are summarized as the daily mean of the continuous total phosphorus loads and are available in NWIS (U.S. Geological Survey, 2023).

With continued discrete sample collection and continuous turbidity monitor operation, the surrogate models may be used beyond the study period that was used to develop them.

Collection of samples throughout the year and during a variety of streamflow conditions along with an annual validation of the regression models to ensure the relation between turbidity and total phosphorus has not significantly changed is warranted. The annual model validation may include plotting new observations with the original model calibration dataset, recomputing the regression coefficients, and determining whether the recomputed coefficients are significantly different than the original coefficients (using an analysis of covariance and probability value significance level of 0.05). The regression models would benefit from continued refinement by the addition of the new data collected each year (Rasmussen and others, 2009).

When a continuous turbidity record was unavailable or when turbidity values were outside of the specified range of the surrogate models, streamflow data were used with the LOADEST model to estimate daily loads of total phosphorus (Runkel and others, 2004). Initially, an alternate surrogate model for each study site was explored for use when a turbidity record was unavailable. Log-transformed streamflow data were fitted to log-transformed total phosphorus concentrations (fig. 1.1). Because of the poor fit between streamflow and total phosphorus concentrations (adjusted coefficient of determination [R^2_a] of 0.243 for the St. Joseph study site and 0.453 for the Hermann study site), the alternate surrogate models for the calculation of continuous total phosphorus concentrations were not further pursued. Rather, the USGS rloadest package (Lorenz and others, 2024), which is the R version of the LOADEST program of Runkel and others (2004), was used to select a streamflow-based model to fill in the gaps of the computed daily total phosphorus load record. This process provided daily loads for days when loads from the turbidity-surrogate model were missing. The rloadest package assists the user in developing an appropriate regression model using explanatory variables that include various functions of streamflow and decimal time for the estimation of total phosphorus concentration and load (Runkel and others, 2004). The input variables for the LOADEST models included total phosphorus concentrations, streamflow, time, and seasonality. Coefficients with probability values less than 0.05 were considered significant. The best predefined model generated using LOADEST was selected based on the AIC value and the comparison of the observed and estimated loads across the range of values.

Water-Quality Sample and Sensor Data

The turbidity values in the calibration dataset well represented the time-series dataset for the St. Joseph study site, with the turbidity values used in the surrogate model calibration dataset ranging from 2.6 to 1,370 formazin nephelometric units (FNUs; median of 44 FNUs; table 2). The time-series (15-minute) turbidity data for the entire study period ranged from 1 to 1,750 FNUs (median of 48 FNUs). Approximately 0.08 percent of the time-series data were below the minimum turbidity in the calibration dataset, and only 0.05 percent of the time-series data were above the maximum turbidity in the calibration dataset (fig. 2). The total phosphorus concentrations ranged from 0.06 to 4.28 mg/L (median of 0.28 mg/L; table 2). The associated streamflows for the calibration dataset ranged from 22,500 to 228,000 cubic feet per second (ft^3/s; median of 46,200 ft^3/s), whereas the time-series streamflow data ranged from 16,800 to 317,000 ft^3/s (median of 46,200 ft^3/s; table 2; fig. 1.2). The input data for rloadest had similar ranges of total phosphorus concentrations and associated streamflows, when compared to the turbidity-surrogate calibration dataset (table 3).

The turbidity values used in the Hermann turbidity-surrogate model ranged from 12.7 to 890 FNUs (median of 95 FNUs; table 2). The time-series (15-minute) turbidity data for the entire study period ranged from 1.2 to 1,690 FNUs (median of 69 FNUs). With approximately 4.10 percent of the time-series data below the minimum turbidity in the calibration dataset and approximately 0.530 percent of the time-series data above the maximum turbidity in the calibration dataset, the calibration dataset did not span the range of observed values at the Hermann study site quite as well as the other study site, which was considered when constraining the model to turbidity values less than or equal to (≤) 890 FNUs (fig. 2). The total phosphorus concentrations ranged from 0.159 to 2.72 mg/L (median of 0.386 mg/L; table 2). The associated streamflows for the calibration dataset ranged from 32,600 to 383,000 ft^3/s (median of 103,000 ft^3/s), whereas the time-series streamflow data ranged from 26,500 to 515,000 ft^3/s (median of 83,600 ft^3/s; table 2; fig. 1.2). The input data for rloadest had similar ranges of total phosphorus concentrations and associated streamflows when compared to the turbidity-surrogate calibration dataset (table 3).

Continuous turbidity records are available for approximately 88 percent of the estimation period (water years 2008 through 2022) for the St. Joseph study site and for approximately 86 percent of the estimation period for the Hermann study site. Gaps in the turbidity record were due to winter conditions, equipment failures, biofouling, and (or) data corrections that exceeded USGS criteria (Wagner and others, 2006).

Table 2. Summary of turbidity-surrogate calibration data and continuous data, Missouri River at St. Joseph and Hermann, Missouri.

[Data are from the U.S. Geological Survey National Water Information System database (U.S. Geological Survey, 2023). mg/L as P, milligram per liter as phosphorus; FNU, formazin nephelometric unit; ft^3/s, cubic feet per second]

Statistic	Sample data[a]		Calibration data and associated streamflow		Overall time-series data during estimation period (October 1, 2007, through September 30, 2022)		Long-term streamflow (ft^3/s)[b]
	Total phosphorus (mg/L as P)	Orthophosphate (mg/L as P)	Turbidity (FNU)	Streamflow (ft^3/s)	Turbidity (FNU)	Streamflow (ft^3/s)	
Missouri River at St. Joseph, Missouri (U.S. Geological Survey station 06818000)—Calibration period November 27, 2008, to August 22, 2022							
Maximum	4.28	0.262	1,370	228,000	1,750	317,000	380,000
99th percentile	2.40	0.229	857	187,000	900	203,000	149,000
98th percentile	2.20	0.201	727	171,000	690	170,000	126,000
75th percentile	0.40	0.13	88	67,700	94	67,800	54,200
Median	0.28	0.096	44	46,200	48	46,200	39,200
25th percentile	0.18	0.072	24.5	39,900	25.5	37,500	27,900
Minimum	0.06	0.026	2.6	22,500	1	16,800	2,300
Count	159	159	159	159	460,366	517,224	34,333
Missouri River at Hermann, Missouri (U.S. Geological Survey station 06934500)—Calibration period April 10, 2008, to July 25, 2022							
Maximum	2.72	0.197	890	383,000	1,690	515,000	739,000
99th percentile	1.88	0.185	761	296,000	780	318,000	322,680
98th percentile	1.70	0.179	713	256,000	651	281,000	274,000
75th percentile	0.541	0.127	195	145,00	170	137,000	104,000
Median	0.386	0.104	95	103,000	69	83,600	62,900
25th percentile	0.253	0.085	45	68,100	31	53,800	43,000
Minimum	0.159	0.015	12.7	32,600	1.2	26,500	4,200
Count	175	173	175	174	447,373	501,933	34,333

[a]Statistics do not include the two outliers excluded from the calibration dataset site (sampled on May 29, 2013, and May 6, 2019) for the Missouri River at Hermann, Missouri.

[b]Long-term streamflow record includes available daily mean streamflow values for October 1, 1928, through September 30, 2022.

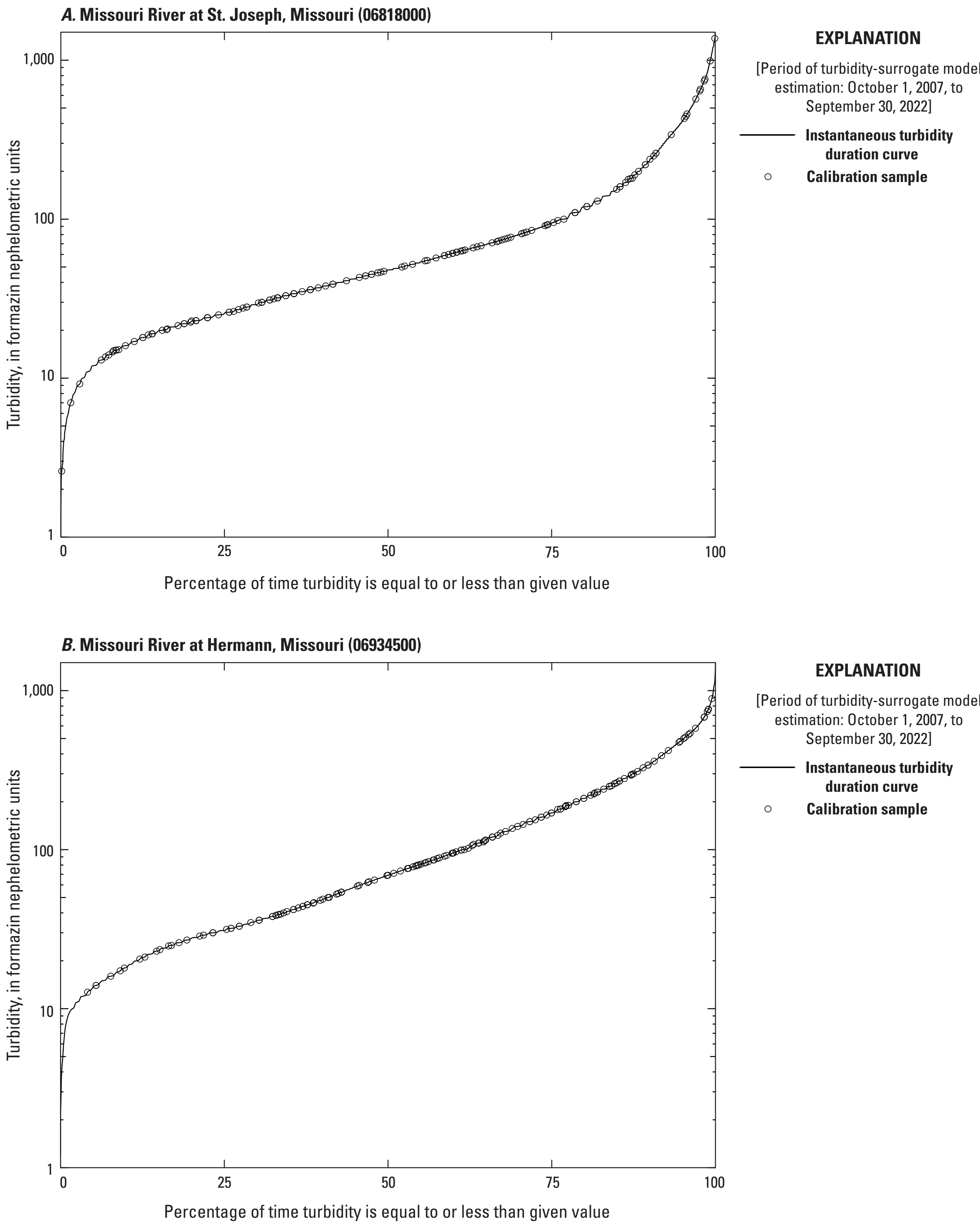

Figure 2. Turbidity duration curves with calibration samples at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

Table 3. Summary of LOAD ESTimator (LOADEST) model input datasets and predicted total phosphorus daily loads for the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

[Input data are from the U.S. Geological Survey National Water Information System database (U.S. Geological Survey, 2023). mg/L as P, milligrams per liter as phosphorus; ft^3/s, cubic feet per second; ton/d as P, U.S. short ton per day as phosphorus]

Statistic	Input data[a]			Predicted total phosphorus, (ton/d as P)
	Total phosphorus (mg/L as P)	Streamflow associated with total phosphorus sample (ft^3/s)	Daily mean streamflow during study period	
Missouri River at St. Joseph, Missouri (U.S. Geological Survey station 06818000)—Calibration period October 19, 2007, to September 20, 2022; estimation period October 1, 2007, to September 30, 2022				
Maximum	4.28	228,000	313,000	773
99th percentile	2.40	186,000	202,000	518
98th percentile	2.19	168,000	169,000	411
75th percentile	0.418	65,300	67,600	91.0
Median	0.280	45,300	46,100	45.5
25th percentile	0.183	38,100	37,400	26.6
Minimum	0.060	18,900	17,000	4.50
Count	174	174	5,479	5,479
Missouri River at Hermann, Missouri (U.S. Geological Survey station 06934500)—Calibration period November 29, 2007, to July 25, 2022; estimation period October 1, 2007, to September 30, 2022				
Maximum	2.72	383,000	492,000	1,710
99th percentile	1.87	291,000	316,000	817
98th percentile	1.66	251,000	280,000	682
75th percentile	0.555	145,000	137,000	202
Median	0.379	102,000	83,800	86.6
25th percentile	0.253	65,500	53,500	40.5
Minimum	0.158	32,600	26,700	12.7
Count	195	195	5,479	5,479

[a]Statistics do not include the two outliers excluded from the calibration dataset (sampled on May 29, 2013, and May 6, 2019) for the Missouri River at Hermann, Missouri.

Surrogate Models

Turbidity-surrogate models for the two study sites were used to calculate total phosphorus concentrations, loads, and yields for the study period. LOADEST was used to fill gaps in the calculated total phosphorus daily load record for days when an adequate turbidity record was not available or when turbidity values were outside of the range specified for the surrogate models. The 15-minute total phosphorus concentrations and the daily loads computed from the turbidity-surrogate models are available in NWIS (U.S. Geological Survey, 2023).

Turbidity-Surrogate Models

Because of curvature in the relation between turbidity and total phosphorus, a quadratic model was chosen for the St. Joseph study site (fig. 3, table 4) based on its low AIC compared to other models. The turbidity-surrogate model for the St. Joseph study site had an R^2_a of 0.885, a root mean square error (RMSE) of 0.137, and a retransformation bias correction factor (BCF) of 1.005 (table 4; figs. 3, 4). The model is applicable to turbidity values ≤1,750, the highest turbidity value in the continuous dataset through water year 2022 (tables 2 and 4).

For the Hermann study site, the calibration dataset was split into two datasets and used to develop two surrogate models based on turbidity magnitudes. A low turbidity model was developed with calibration data ≤125 FNUs, and a high turbidity model was developed with calibration data greater than 125 and ≤890 FNUs (the highest turbidity value in the calibration dataset). Curvature between turbidity and total phosphorus also resulted in the selection of a quadratic model for the low and high turbidity datasets (fig. 3, table 4). The low turbidity model for the Hermann study site had an R^2_a of 0.690, an RMSE of 0.057, and a BCF of 1.003. The high turbidity model had an R^2_a of 0.740, an RMSE of 0.222, and a BCF of 1.004 (table 4; figs. 3, 4).

Table 4. Total phosphorus turbidity-surrogate models at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

[Dates are shown in month/day/year format. USGS, U.S. Geological Survey; R^2_a, adjusted coefficient of determination; RMSE, root mean square error; BCF, bias correction factor; *n*, count; ≤, less than or equal to; log, logarithm; *TP*, total phosphorus concentration, in milligrams per liter; *Turb*, turbidity, in formazin nephelometric units; >, greater than]

USGS station	Start date of calibration dataset	End date of calibration dataset	Applicable range	Surrogate model	Model diagnostics			
					R^2_a	RMSE	BCF	*n*
Missouri River at St. Joseph, Missouri (06818000)	11/27/2007	9/20/2022	Turbidity ≤ 1,750	$\log(TP)=0.17869\times\log(Turb)^2-0.05172\times\log(Turb)-0.98499$	0.885	0.137	1.005	159
Missouri River at Hermann, Missouri (06934500)	4/10/2008	7/25/2022	Turbidity ≤ 125	$\log(TP)=0.3307\times\log(Turb)^2-0.6539\times\log(Turb)-0.4147$	0.690	0.057	1.003	111
			Turbidity > 125 and ≤ 890	$\log(TP)=0.5299\times\log(Turb)^2-1.9133\times\log(Turb)+1.3361$	0.740	0.222	1.004	64

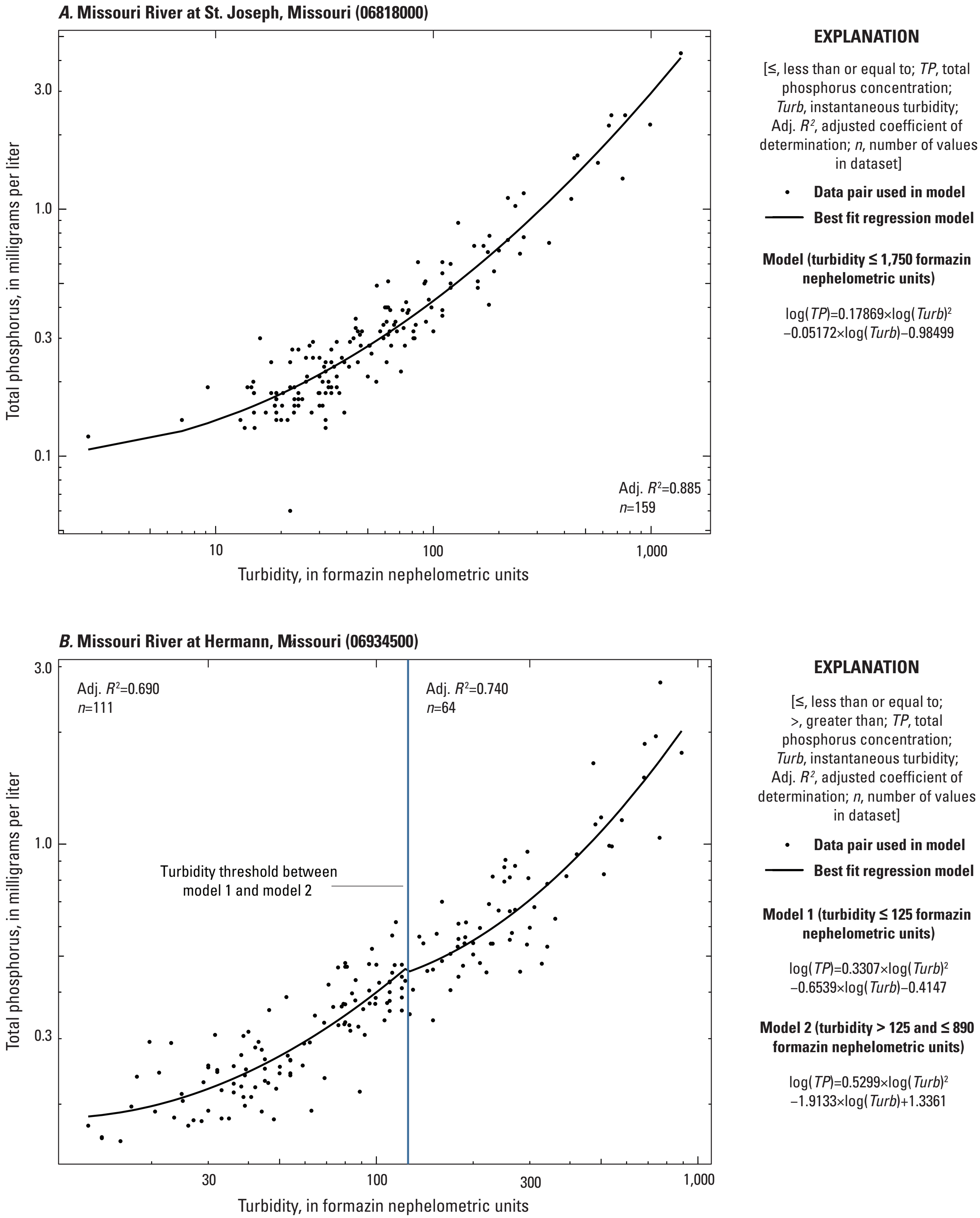

Figure 3. Total phosphorus turbidity-surrogate models at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

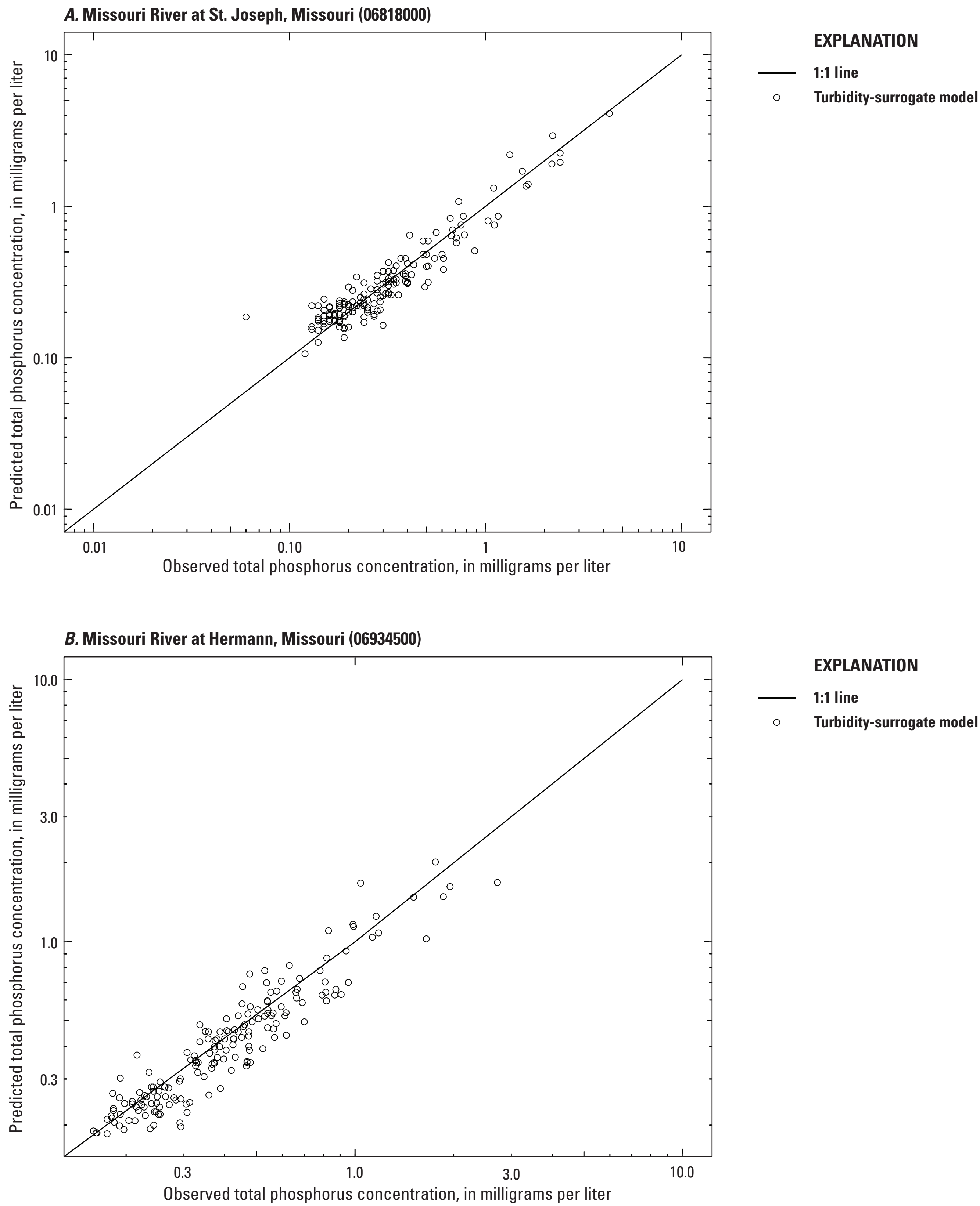

Figure 4. Observed and computed total phosphorus concentrations at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

Quadratic models were chosen for both sites owing to larger residuals on the low and high ends that were not explained by other available parameters and that are likely controlled by different processes. When compared to linear models and models including additional explanatory variables (for example, temperature and streamflow), the quadratic models for both study sites had the lowest AIC. It is hypothesized that the curvature in the turbidity and total phosphorus relation at lower values is due to baseline total phosphorous contributions even during low turbidity and low flow conditions. Both study sites exhibited higher ratios of orthophosphate to total phosphorus during low turbidity conditions, with less of the total phosphorus attributed to orthophosphate during higher turbidity conditions (fig. 5). At the higher values of the turbidity and total phosphorus relation, it is hypothesized that the curvature is due to changes in the chemical or physical composition of the suspended sediment during high flow and high turbidity conditions. Both sites exhibited more consistent increased percentage of fine particles (less than 0.063 millimeter) at higher turbidity values (fig. 6), which are associated with higher total phosphorus concentrations, whereas larger particle sizes (described as percentage of coarse particles) are generally associated with lower total phosphorus concentrations (Capasso and others, 2020).

No outliers were excluded from the turbidity-surrogate model for the St. Joseph study site, whereas two outliers were excluded from the model for the Hermann study site. The outliers occurred on May 29, 2013 (turbidity=570 FNUs and total phosphorus less than 0.01 mg/L), and May 6, 2019 (turbidity=165 FNUs and total phosphorus=0.105 mg/L), and were excluded owing to undue influence on the model. The outliers did not represent extremes in turbidity or streamflow; thus, their exclusion did not constrain the models. These same outliers were also omitted from the input for the LOADEST calculations for the Hermann study site.

Supplemental LOAD ESTimator Model

The turbidity-surrogate models were used to estimate total phosphorus concentrations at the study sites (table 5). A regression model (LOADEST) that uses streamflow as the independent variable can supplement the surrogate model to obtain a complete total phosphorus record. When the turbidity record was unavailable or when values were outside of the specified ranges for the models (413 of the 5,479 days for the St. Joseph study site and 678 of the 5,479 days for the Hermann study site), rloadest regression equations were used to calculate daily total phosphorus loads for a more complete total phosphorus load record (table 5). Seasonal variables were significant and were included in the equation for the St. Joseph study site because total phosphorus followed a seasonal pattern at that site. The seasonal terms did not have the best fit for the Hermann study site and thus were not included in the LOADEST regression model (fig. 7). The rloadest regression equations had R^2_a of 0.73 and 0.83 for the St. Joseph and Hermann study sites, respectively. Both sites had overall negative load biases, with a larger bias at the St. Joseph study site (−12.43 percent) than the Hermann study site (−2.195 percent) (table 5).

Computed Total Phosphorus Concentrations, Loads, and Yields

During the 15-year study period for the St. Joseph study site, daily mean total phosphorus concentrations calculated using the surrogate model ranged from 0.104 to 4.56 mg/L (median of 0.272 mg/L and mean of 0.417 mg/L; table 6). Computed total phosphorus daily loads from the turbidity-surrogate model (with gaps in record filled with LOADEST data) ranged from 5.19 to 1,760 tons/d (median of 36.5 tons/d and mean of 79.8 tons/d), and daily yields ranged from 0.0243 to 8.24 pounds per square mile per day (lb/mi^2/d; median of 0.171 lb/mi^2/d and mean of 0.374 lb/mi^2/d). Depending on the year, 67.1 to 100 percent of the daily loads were computed using the surrogate model, with 92.4 percent of the total load for the 15-year period calculated using the surrogate model (table 6).

From the surrogate model with gaps filled with LOADEST models, annual total phosphorus loads at the St. Joseph study site ranged from 9,570 tons in water year 2022 to 50,500 tons in water year 2019 (total load for the study period of 437,000 tons), and annual yields ranged from 44.9 pounds per square mile per year (lb/mi^2/yr) in water year 2022 to 237 lb/mi^2/yr in water year 2019 (total yield for entire study period of 137 lb/mi^2/yr; table 6, fig. 8).

For comparison purposes, total phosphorus loads computed only using LOADEST models were compared to the annual load calculated using the surrogate model for water year 2018 because it had a complete daily load record and did not require gaps to be filled with LOADEST data. The annual load calculated using the surrogate model for water year 2018 was 24,600 tons, and the annual load calculated using only LOADEST data was 27,600 tons (11.5-percent difference; Markland, 2024). Despite different inputs for these two models, the annual loads are within less than 15 percent of one another, which lends credence to the models. Total phosphorus concentrations, loads, and yields estimated using turbidity as the independent variable in the surrogate models are preferentially used instead of those using flow in the LOADEST models because total phosphorus concentrations are more highly correlated with turbidity than with flow. Estimates from the LOADEST models were used when turbidity data were not available.

For the Hermann study site, daily mean total phosphorus concentrations calculated using only surrogate regression models ranged from 0.183 to 1.97 mg/L (median of 0.319 mg/L and mean of 0.421 mg/L; table 6). Computed total phosphorus daily loads from the turbidity-surrogate model (with gaps in record filled with LOADEST data) ranged from 12.7 to 1,970 tons/d (median of 76.8 tons/d and mean of 152 tons/d), and daily yields ranged from 0.0486 to 7.55 lb/mi^2/d (median of 0.294 lb/mi^2/d and mean of 0.582 lb/mi^2/d). Depending on the year, 54.1 to 100

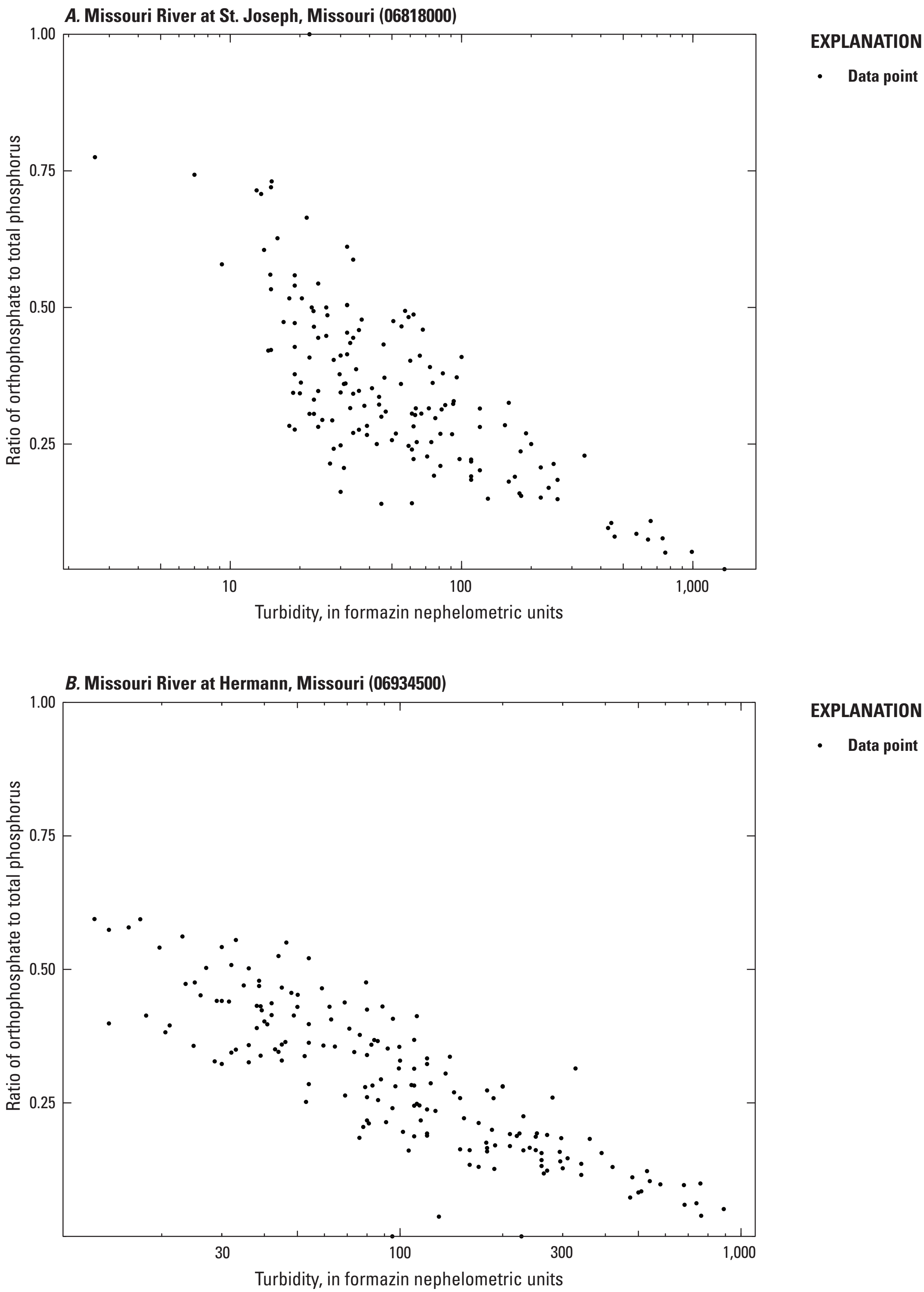

Figure 5. Relation between turbidity and the ratio of orthophosphate to total phosphorus at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

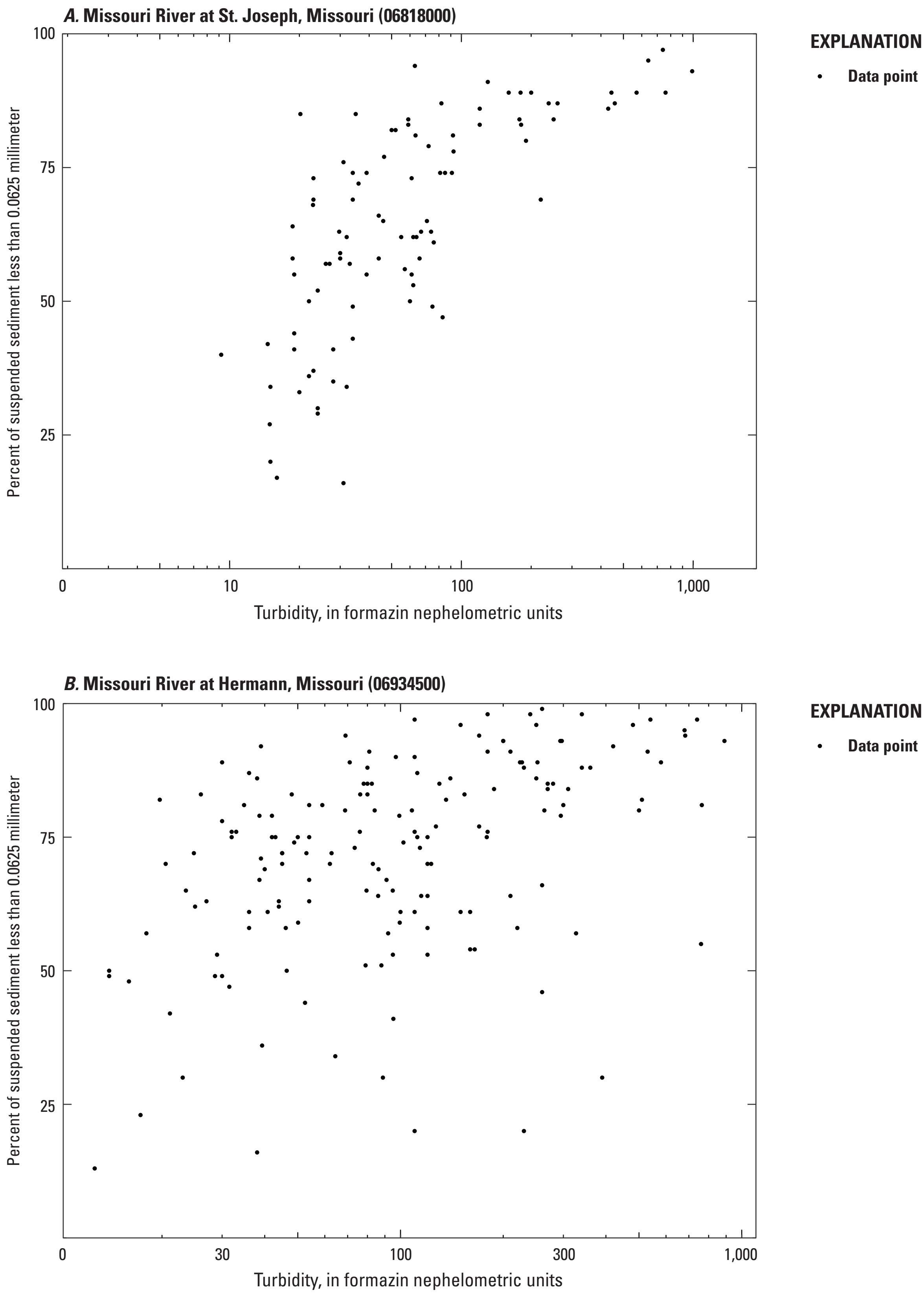

Figure 6. Relation between turbidity and the percentage of suspended sediment less than 0.0625 millimeter at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

Table 5. Total phosphorus LOAD ESTimator (LOADEST) models at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

[Dates are shown in month/day/year format. USGS, U.S. Geological Survey; R^2_a, adjusted coefficient of determination; ln, natural logarithm; *TPL*, total phosphorus load, in kilograms per day; ln, natural logarithm; ln*Q*, ln(streamflow, in cubic feet per second)−center of ln(streamflow, in cubic feet per second); *dtime*, decimal time−center of decimal time; LOADEST, LOAD ESTimator]

USGS station	Start date of calibration dataset	End date of calibration dataset	Model[b]	Diagnostics		
				R^2_a	Residual variance	Load bias (percent)[a]
Missouri River at St. Joseph, Missouri (06818000)	10/19/2007	9/20/2022	$\ln(TPL)=1.70068\times\ln Q-0.20295\times\ln Q^2-0.04334\times dtime+0.28271\times\sin(2\pi\times dtime)-0.14943\times\cos(2\pi\times dtime)+10.96911$	0.73	0.2943	−12.43
Missouri River at Hermann, Missouri (06934500)	11/29/2007	7/25/2022	$\ln(TPL)=1.69824\times\ln Q-0.01409\times dtime+11.50614$	0.83	0.1673	−2.195

[a]A negative load bias indicates an underestimation, when comparing estimated loads and observed loads for days when concentration data are available.

[b]LOAD ESTimator (LOADEST) model does not include the two outliers identified during the turbidity-surrogate calibration dataset (sampled on May 29, 2013, and May 6, 2019) for the Missouri River at Hermann, Missouri.

percent of the daily loads were computed using the surrogate model, with 87.6 percent of the total load for the 15-year period calculated using the surrogate model (table 6).

Annual loads at the Hermann study site were approximately twice as much as those computed for the St. Joseph study site, ranging from 22,600 tons in water year 2022 to 101,000 tons in water year 2019 (total load for the study period of 833,000 tons; table 6, fig. 8). Annual yields ranged from 86.7 lb/mi^2/yr in water year 2022 to 385 lb/mi^2/yr in water year 2019 (total yield for entire study period of 213 lb/mi^2/yr; table 6). For comparison purposes, total phosphorus loads computed using LOADEST were compared to the annual load calculated using the surrogate model for water year 2018 because it had a complete daily load record and did not require gaps to be filled with LOADEST data. The annual load calculated using the surrogate model for water year 2018 was 34,000 tons, and the annual load calculated using LOADEST was 30,700 tons (10.2-percent difference; Markland, 2024).

Because the Hermann study site is a USGS NWQN monitoring location, additional concentration and load estimates, as well as long-term trend information, are available using other methods for comparison to the concentrations and loads calculated in this report. Weighted regressions on time, discharge, and season (WRTDS) software has been used to calculate flow-normalized (removes effects of flow-related variability to aid in long-term trend analysis) total phosphorus loads at the Hermann study site since 1970, with results available through NWQN (U.S. Geological Survey, 2022). Discharge, as used in WRTDS, is the same as streamflow. For annual flow-normalized total phosphorus loads, a 3-percent decrease (attributed to changes in the watershed that were not streamflow-related) was observed for the period from 1982 to 2022. As for more recent trend periods, a 38-percent decrease and a 24-percent decrease were observed from 2002 to 2022 and from 2012 to 2022, respectively. As for annual loads of total phosphorus, approximately 716,000 tons of total phosphorus were calculated using the WRTDS model in water years 2008 through 2022 (U.S. Geological Survey, 2022), compared to the 833,000 tons calculated in this report (a 15.1-percent difference). The differences between various methods used to estimate total phosphorus loads have been explored, with total phosphorus being one of the more difficult constituents for which to accurately estimate annual loads (Lee and others, 2016, 2019). Because most of total phosphorus can often be transported during a small number of larger hydrologic events, it can be difficult to accurately estimate loads with discrete sampling methods when those events are not sampled (Lee and others, 2019). Conversely, the use of continuous turbidity monitor data and surrogate models can often better capture the range of hydrologic conditions and these larger events, which can result in the differences between methods in annual load estimations.

The sources of nutrient loads and yields from major subbasins within the Missouri River drainage basin were investigated using SPAtially Referenced Regressions On Watershed attributes (SPARROW models by Brown and others (2011). The total phosphorus load delivered to the Mississippi River from the Missouri River was estimated at approximately 43,000 tons per year (loads detrended to the base year 2002; Brown and others, 2011). The largest proportion of total phosphorus was contributed by the Middle Missouri and Lower Missouri subbasins (18.6 and 38.7 percent, respectively). The smallest proportions were delivered by the Upper Missouri and Yellowstone subbasins (0.1 percent each; Brown and others, 2011).

Although these studies of total phosphorus loading in the Missouri River provide important information, the use of turbidity time-series data in surrogate models improves the ability to estimate total phosphorus loads (Schilling and others,

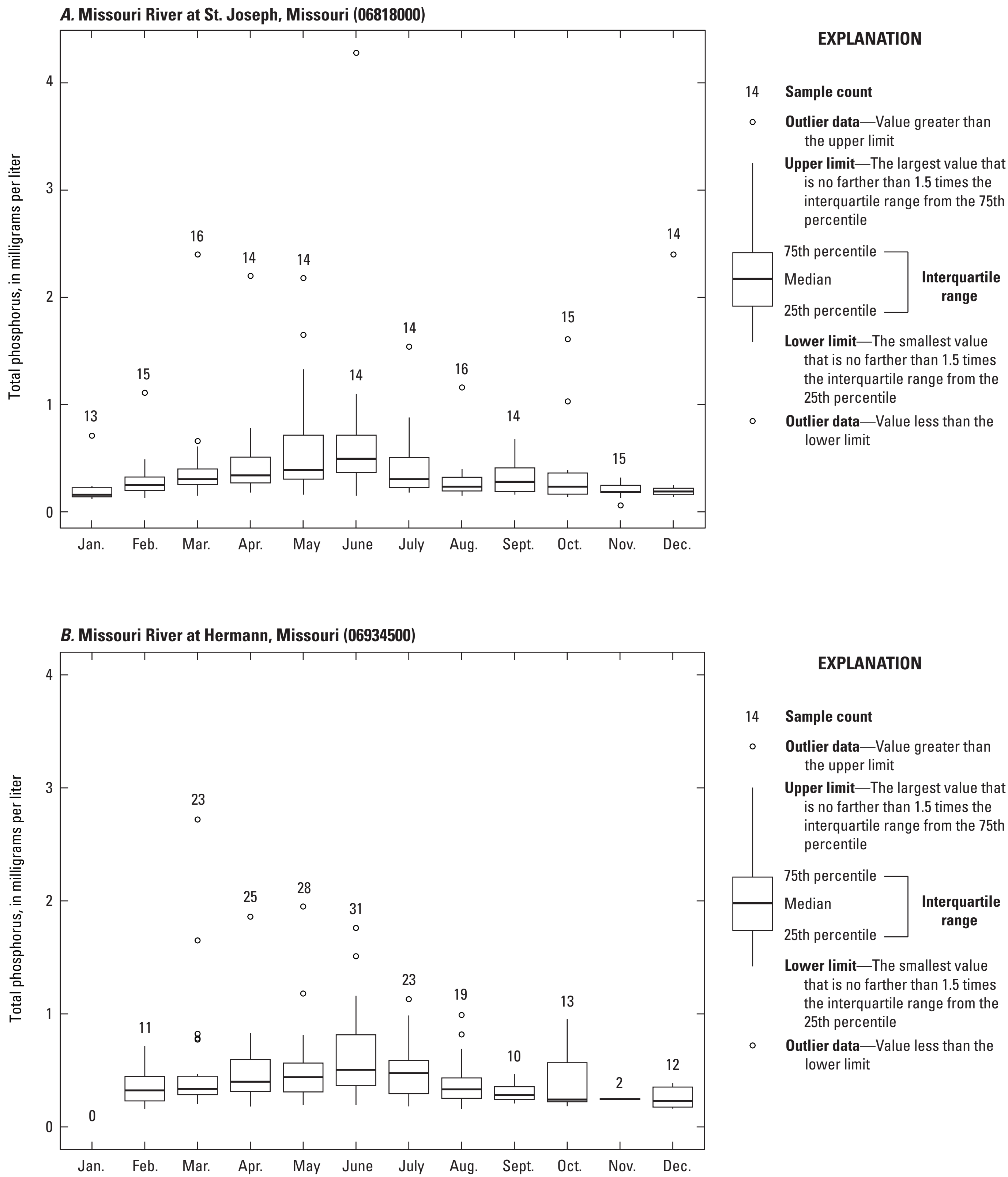

Figure 7. Total phosphorus concentrations by month at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

Table 6. Summary of total phosphorus concentrations, loads, and yields at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

[mg/L, milligram per liter; ton/d, U.S. short ton per day; lb/mi²/d, pound per square mile per day; lb/mi²/yr, pound per square mile per year; Max, maximum; Min, minimum; --, no data; LOADEST, LOAD ESTimator]

Water year	Daily mean concentration (mg/L)[a]				Daily load (ton/d)[b]				Daily yield (lb/mi²/d)				Daily loads computed using surrogate model		Annual load (ton)	Annual yield (lb/mi²/yr)
	Mean	Median	Max	Min	Mean	Median	Max	Min	Mean	Median	Max	Min	Count	Percent		
Missouri River at St. Joseph, Missouri (U.S. Geological station 06818000)—Surrogate model only																
2008	0.646	0.354	4.56	0.126	113	36.7	1,760	8.10	0.530	0.172	8.24	0.0380	340	93.2	38,400	180
2009	0.644	0.409	3.57	0.248	89.9	45.7	761	15.3	0.423	0.214	3.57	0.0715	245	67.1	22,000	103
2010	0.551	0.439	2.40	0.218	129	93.8	603	24.4	0.606	0.440	2.83	0.114	235	64.4	30,400	143
2011	0.349	0.320	1.99	0.135	98.3	84.0	637	13.9	0.461	0.394	2.99	0.0651	346	94.8	34,000	160
2012	0.350	0.262	3.60	0.171	48.5	35.4	894	15.2	0.227	0.166	4.19	0.0714	360	98.4	17,500	81.9
2013	0.405	0.246	3.89	0.138	57.7	24.3	1,380	7.81	0.271	0.114	6.47	0.0366	333	91.2	19,200	90.1
2014	0.623	0.302	4.11	0.121	98.9	28.2	1,390	5.97	0.464	0.132	6.51	0.0280	354	97.0	35,000	164
2015	0.514	0.278	3.20	0.145	99.2	41.6	1,150	10.7	0.465	0.195	5.37	0.0504	318	87.1	31,500	148
2016	0.502	0.332	2.59	0.169	96.1	48.9	886	21.1	0.451	0.229	4.15	0.0991	363	99.2	34,900	164
2017	0.334	0.240	2.15	0.126	54.6	30.9	745	10.2	0.256	0.145	3.50	0.0480	359	98.4	19,600	91.9
2018	0.325	0.270	1.78	0.105	67.5	51.6	618	8.87	0.317	0.242	2.90	0.0416	365	100	24,600	116
2019	0.390	0.284	2.62	0.129	134	87.9	1,210	13.6	0.628	0.412	5.68	0.0639	359	98.4	48,100	226
2020	0.302	0.229	1.49	0.135	66.6	53.3	506	17.6	0.312	0.250	2.38	0.0825	364	99.5	24,200	114
2021	0.250	0.188	2.84	0.130	32.9	21.1	902	9.15	0.154	0.0989	4.23	0.0429	364	99.7	12,000	56.1
2022	0.240	0.178	1.81	0.104	26.2	17.4	351	5.19	0.123	0.0816	1.65	0.0243	360	98.6	9,440	44.2
2008–22	0.417	0.272	4.56	0.104	79.2	37.9	1,760	5.19	0.371	0.178	8.24	0.0243	5,070	92.4	401,000	125
Missouri River at St. Joseph, Missouri (U.S. Geological station 06818000)—Surrogate model with gaps filled with LOADEST data																
2008	--	--	--	--	113	38.6	1,760	8.10	0.532	0.181	8.24	0.0380	--	--	41,400	194
2009	--	--	--	--	67.6	38.3	761	6.09	0.318	0.180	3.57	0.0285	--	--	24,700	116
2010	--	--	--	--	117	67.0	603	11.7	0.550	0.314	2.83	0.0547	--	--	42,800	201
2011	--	--	--	--	126	91.3	773	13.9	0.593	0.428	3.62	0.0651	--	--	46,100	216
2012	--	--	--	--	48.6	35.4	894	15.2	0.228	0.166	4.19	0.0715	--	--	17,800	83.4
2013	--	--	--	--	54.8	24.3	1,380	7.81	0.257	0.114	6.47	0.0366	--	--	20,000	93.7
2014	--	--	--	--	96.2	27.2	1,390	5.94	0.451	0.128	6.51	0.0280	--	--	35,100	165
2015	--	--	--	--	91.0	36.5	1,150	10.7	0.427	0.171	5.37	0.0504	--	--	33,200	156
2016	--	--	--	--	95.9	49.3	886	21.1	0.450	0.231	4.15	0.0991	--	--	35,100	165
2017	--	--	--	--	54.0	30.4	745	10.2	0.253	0.143	3.50	0.0480	--	--	19,700	92.5

Table 6. Summary of total phosphorus concentrations, loads, and yields at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).—Continued

[mg/L, milligram per liter; ton/d, U.S. short ton per day; lb/mi²/d, pound per square mile per day; lb/mi²/yr, pound per square mile per year; Max, maximum; Min, minimum; --, no data; LOADEST, LOAD ESTimator]

Water year	Daily mean concentration (mg/L)[a]				Daily load (ton/d)[b]				Daily yield (lb/mi²/d)				Daily loads computed using surrogate model		Annual load (ton)	Annual yield (lb/mi²/yr)
	Mean	Median	Max	Min	Mean	Median	Max	Min	Mean	Median	Max	Min	Count	Percent		
Missouri River at St. Joseph, Missouri (U.S. Geological station 06818000)—Surrogate model with gaps filled with LOADEST data—Continued																
2018	--	--	--	--	67.5	51.6	618	8.87	0.317	0.242	2.90	0.0416	--	--	24,600	116
2019	--	--	--	--	138	87.9	1,210	13.6	0.648	0.412	5.68	0.0639	--	--	50,500	237
2020	--	--	--	--	67.1	53.5	506	17.6	0.315	0.251	2.37	0.0826	--	--	24,600	115
2021	--	--	--	--	32.8	21.1	902	9.15	0.154	0.0988	4.23	0.0429	--	--	12,000	56.2
2022	--	--	--	--	26.2	17.5	351	5.19	0.123	0.0820	1.65	0.0243	--	--	9,570	44.9
2008–22	--	--	--	--	79.8	36.5	1,760	5.19	0.374	0.171	8.24	0.0243	--	--	437,000	137
Missouri River at Hermann, Missouri (U.S. Geological Survey station 0693450)—Surrogate model only																
2008	0.549	0.466	1.73	0.198	254	141	1,260	22.4	0.973	0.541	4.82	0.0858	198	54.1	50,400	193
2009	0.555	0.450	1.97	0.197	211	127	1,390	24.2	0.809	0.487	5.32	0.0926	232	63.6	49,100	188
2010	0.566	0.531	1.48	0.223	276	213	1,060	34.6	1.06	0.817	4.07	0.132	212	58.1	58,600	224
2011	0.407	0.378	1.65	0.185	187	138	1,190	23.0	0.715	0.527	4.56	0.0881	322	88.2	60,100	230
2012	0.301	0.225	1.64	0.184	65.0	37.2	508	24.1	0.249	0.142	1.95	0.0924	339	92.6	22,100	84.4
2013	0.359	0.236	1.81	0.183	115	30.7	1,979	13.3	0.441	0.118	7.56	0.0510	341	93.4	39,200	150
2014	0.448	0.274	1.88	0.183	111	39.0	949	15.0	0.424	0.149	3.63	0.0475	316	86.6	35,000	134
2015	0.485	0.298	1.81	0.183	187	59.1	1,300	19.2	0.716	0.226	4.96	0.0734	356	97.5	66,600	255
2016	0.493	0.407	1.90	0.203	176	97.4	1,250	29.3	0.675	0.373	4.80	0.112	349	95.4	61,500	236
2017	0.377	0.271	1.69	0.184	122	51.1	998	20.2	0.468	0.196	3.82	0.0772	356	97.5	43,500	167
2018	0.370	0.304	1.66	0.183	93.1	72.9	746	17.3	0.356	0.279	2.85	0.0661	365	100	34,000	130
2019	0.479	0.388	1.95	0.202	276	201	1,550	42.9	1.06	0.768	5.94	0.164	364	99.7	100,000	384
2020	0.457	0.441	1.43	0.195	185	161	876	26.6	0.707	0.616	3.35	0.102	357	97.5	65,900	252
2021	0.335	0.240	1.49	0.184	111	44.9	1,220	15.0	0.425	0.172	4.66	0.0573	346	94.8	38,400	147
2022	0.286	0.224	1.00	0.183	63.5	31.7	512	14.7	0.243	0.122	1.96	0.0562	348	95.3	22,100	84.6
2008–22	0.421	0.319	1.97	0.183	156	78.5	1,970	13.3	0.595	0.301	7.56	0.0510	4,800	87.6	747,000	191

Table 6. Summary of total phosphorus concentrations, loads, and yields at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).—Continued

[mg/L, milligram per liter; ton/d, U.S. short ton per day; lb/mi²/d, pound per square mile per day; lb/mi²/yr, pound per square mile per year; Max, maximum; Min, minimum; --, no data; LOADEST, LOAD ESTimator]

Water year	Daily mean concentration (mg/L)[a]				Daily load (ton/d)[b]				Daily yield (lb/mi²/d)				Daily loads computed using surrogate model		Annual load (ton)	Annual yield (lb/mi²/yr)
	Mean	Median	Max	Min	Mean	Median	Max	Min	Mean	Median	Max	Min	Count	Percent		
Missouri River at Hermann, Missouri (U.S. Geological Survey station 0693450)—Surrogate model with gaps filled with LOADEST data																
2008	--	--	--	--	196	100	1,260	20.7	0.751	0.383	4.82	0.0791	--	--	71,800	275
2009	--	--	--	--	164	74.7	1,390	24.2	0.626	0.286	5.32	0.0926	--	--	59,700	228
2010	--	--	--	--	259	193	1,060	34.6	0.991	0.739	4.07	0.132	--	--	94,500	362
2011	--	--	--	--	177	130	1,190	23.0	0.679	0.497	4.56	0.0881	--	--	64,800	248
2012	--	--	--	--	67.9	40.1	508	24.1	0.260	0.154	1.94	0.0924	--	--	24,900	95.2
2013	--	--	--	--	109	30.3	1,970	13.3	0.418	0.116	7.55	0.0510	--	--	39,900	153
2014	--	--	--	--	102	35.6	949	12.7	0.392	0.136	3.63	0.0486	--	--	37,400	143
2015	--	--	--	--	188	59.6	1,300	19.2	0.720	0.228	4.96	0.0734	--	--	68,600	263
2016	--	--	--	--	176	97.7	1,250	29.3	0.672	0.374	4.80	0.112	--	--	64,200	246
2017	--	--	--	--	121	54.2	998	20.2	0.464	0.208	3.82	0.0772	--	--	44,300	170
2018	--	--	--	--	93.1	72.9	746	17.3	0.356	0.279	2.85	0.0661	--	--	34,000	130
2019	--	--	--	--	276	202	1,550	42.9	1.06	0.774	5.94	0.164	--	--	101,000	385
2020	--	--	--	--	181	158	876	26.6	0.693	0.606	3.35	0.102	--	--	66,300	254
2021	--	--	--	--	109	46.7	1,220	15.0	0.416	0.179	4.66	0.0573	--	--	39,800	152
2022	--	--	--	--	62.0	31.4	512	14.7	0.237	0.120	1.96	0.0562	--	--	22,600	86.7
2008–22	--	--	--	--	152	76.8	1,970	12.7	0.582	0.294	7.55	0.0486	--	--	833,000	213

[a]Daily mean concentration calculated for days when 80 percent or more of the calculated instantaneous total phosphorus record (15-minute data) was available.

[b]Daily load calculated from the instantaneous daily load record (15-minute data) for days when 48 percent or more of the record was available.

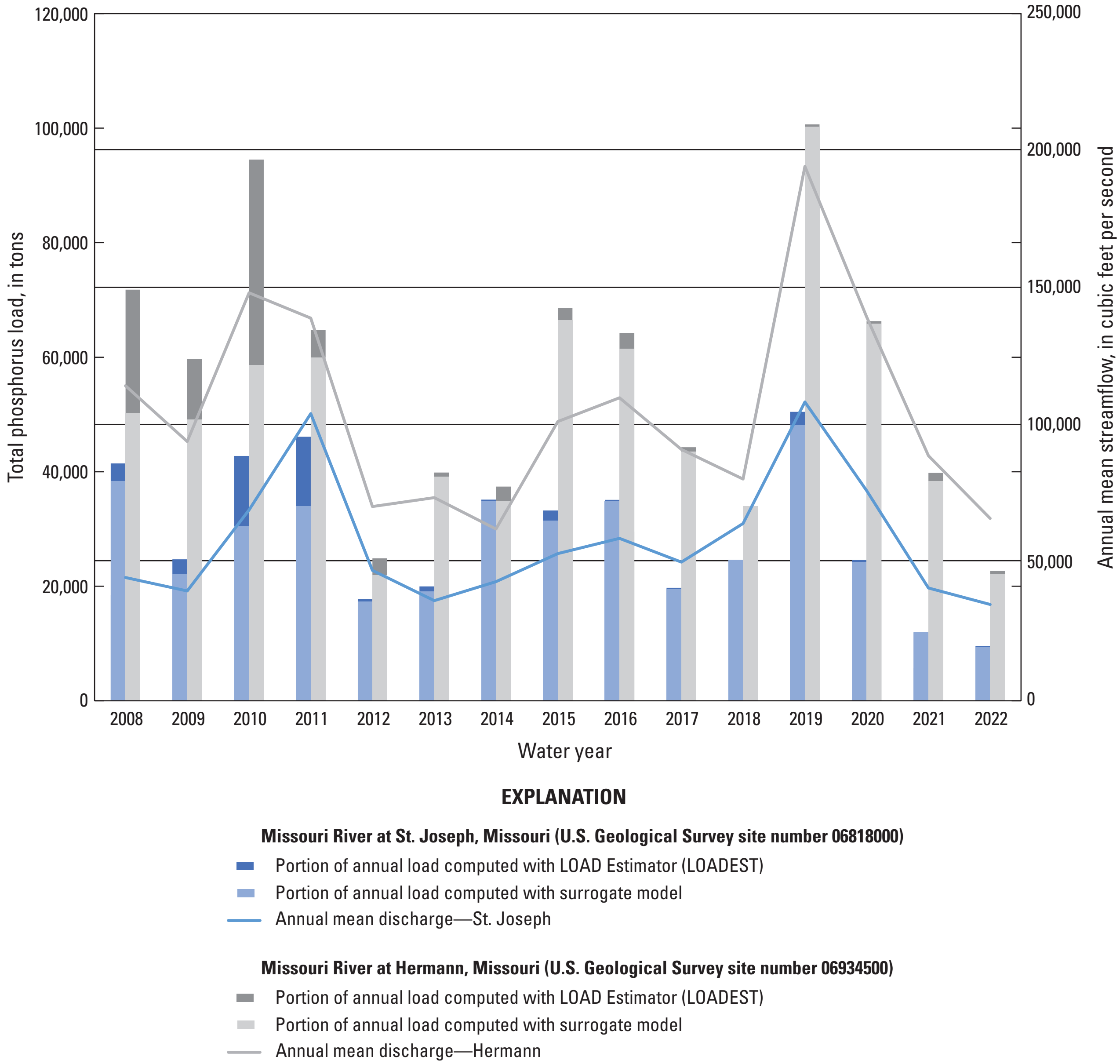

Figure 8. Estimated total phosphorus annual loads for water years 2008–22 at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

2017). The use of continuous data allows for the capture of variability in nutrient transport during the full range of hydrologic conditions, which is not easily done by discrete sampling (Stutter and others, 2017; Villa and others, 2019). Using turbidity as a surrogate allows monitoring of total phosphorus, which is not practical to measure in a field setting, in a way that captures the concentrations and loads of total phosphorus in the Missouri River. The ability to calculate total phosphorus loads is critical in assessing progress towards nutrient reduction goals.

Summary

The U.S. Geological Survey (USGS) and the Missouri Department of Natural Resources collaborated to model total phosphorus concentrations and loads in the Missouri River at St. Joseph, Missouri, streamgage (USGS station 06818000; hereafter referred to as the “St. Joseph study site”), and the Missouri River at Hermann, Mo., streamgage (USGS station 06934500; hereafter referred to as the “Hermann study site”). The Missouri Nutrient Loss Reduction Strategy (NLRS) was created by the Missouri Department of Natural Resources to reduce the nutrient contamination of Missouri’s waterways from point and nonpoint sources, and the Missouri Department of Natural Resources expends considerable resources on the monitoring of water quality in streams throughout the State. Advances in technology have resulted in the ability to directly measure some nutrients, such as nitrate, in real time using direct-read sensors; however, technological advances in measuring total phosphorus concentrations in real time have not progressed as quickly.

To estimate total phosphorus concentrations and loads at the St. Joseph and Herman study sites, turbidity-surrogate models were developed for each site. Quadratic models were chosen for both sites owing to larger residuals on the low and high ends that were not explained by other available parameters. When turbidity data were unavailable or when turbidity values were outside of the specified ranges of the models, LOAD ESTimator (LOADEST) was used to develop regression models based on streamflow data to estimate daily loads of total phosphorus, and these estimates were used to fill the gaps in the calculated total phosphorus load record. This report describes the surrogate models developed to compute total phosphorus concentrations and loads for the St. Joseph and Hermann study sites for water years 2008 to 2022 (October 1, 2007, to September 30, 2022). With ongoing model evaluation and maintenance, the surrogate models may be useful in the future for computing total phosphorus concentrations and loads for the deployment periods beginning in October 2007.

During the 15-year study period for the St. Joseph site, daily mean total phosphorus concentrations calculated using the surrogate model ranged from 0.104 to 4.56 milligrams per liter (mg/L; median of 0.272 mg/L and mean of 0.417 mg/L). Computed total phosphorus daily loads from the turbidity-surrogate model (with gaps in record filled with LOADEST data) ranged from 5.19 to 1,760 tons per day (tons/d; median of 36.5 tons/d and mean of 79.8 tons/d), and daily yields ranged from 0.0243 to 8.24 pounds per square mile per day (lb/mi^2/d; median of 0.171 lb/mi^2/d and mean of 0.374 lb/mi^2/d). Annual loads ranged from 9,570 tons in water year 2022 to 50,500 tons in water year 2019 (total load for the study period of 437,000 tons).

For the Hermann study site, daily mean total phosphorus concentrations calculated using the surrogate regression models ranged from 0.183 to 1.97 mg/L (median of 0.319 mg/L and mean of 0.421 mg/L). Computed total phosphorus daily loads from the turbidity-surrogate model (with gaps in record filled with LOADEST data) ranged from 12.7 to 1,970 tons/d (median of 76.8 tons/d and mean of 152 tons/d), and daily yields ranged from 0.0486 to 7.55 lb/mi^2/d (median of 0.294 lb/mi^2/d and mean of 0.582 lb/mi^2/d). Annual loads ranged from 22,600 tons in water year 2022 to 101,000 tons in water year 2019 (total load for the study period of 833,000 tons).

The ability to calculate total phosphorus loads for the Missouri River is critical in assessing progress towards nutrient reduction goals. The use of continuous data and surrogate models allows for the capture of variability in nutrient transport during the full range of hydrologic conditions, which is not easily done by discrete sampling. Ongoing continuous monitoring of the Missouri River to maintain these models and their concentration and load estimations, along with discrete sampling for nutrients and other water-quality parameters, is warranted.

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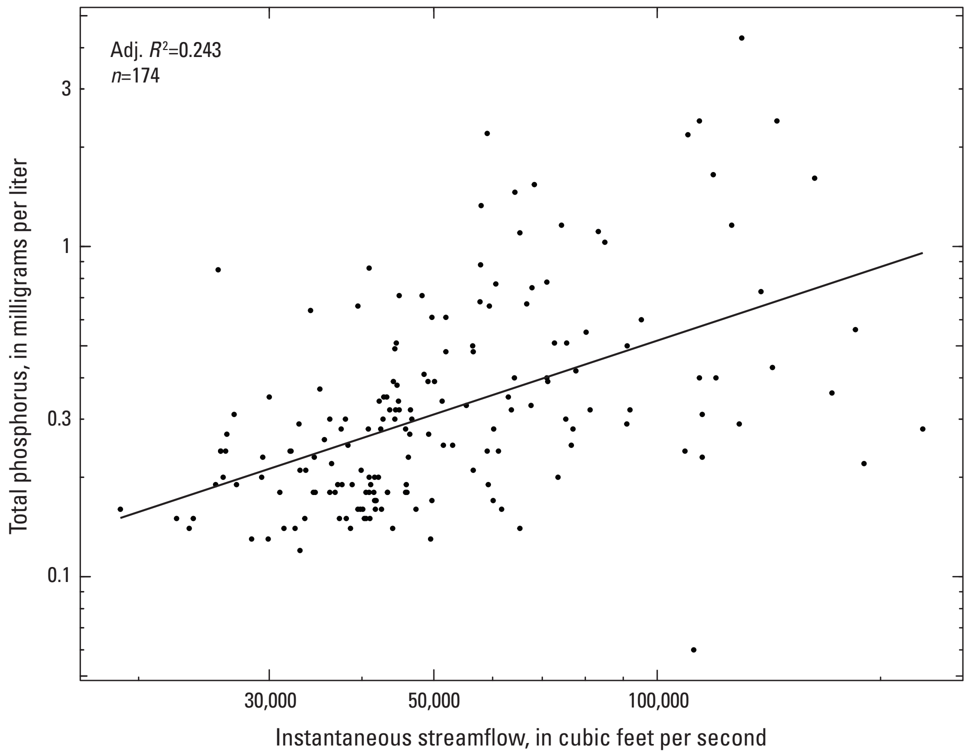
Appendix 1. Supplemental Figures

This appendix provides additional figures that describe streamflow with respect to total phosphorus calibration samples at the Missouri at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500). Streamflow-surrogate regression models were considered, although not ultimately used, for both streamgage sites. The model information is included in these appendix figures for informational purposes.

***A.* Missouri River at St. Joseph, Missouri (06818000)**



EXPLANATION

[*TP*, total phosphorus concentration; Adj. R^2, adjusted coefficient of determination; *n*, number of values in dataset; *Q*, instantaneous streamflow]

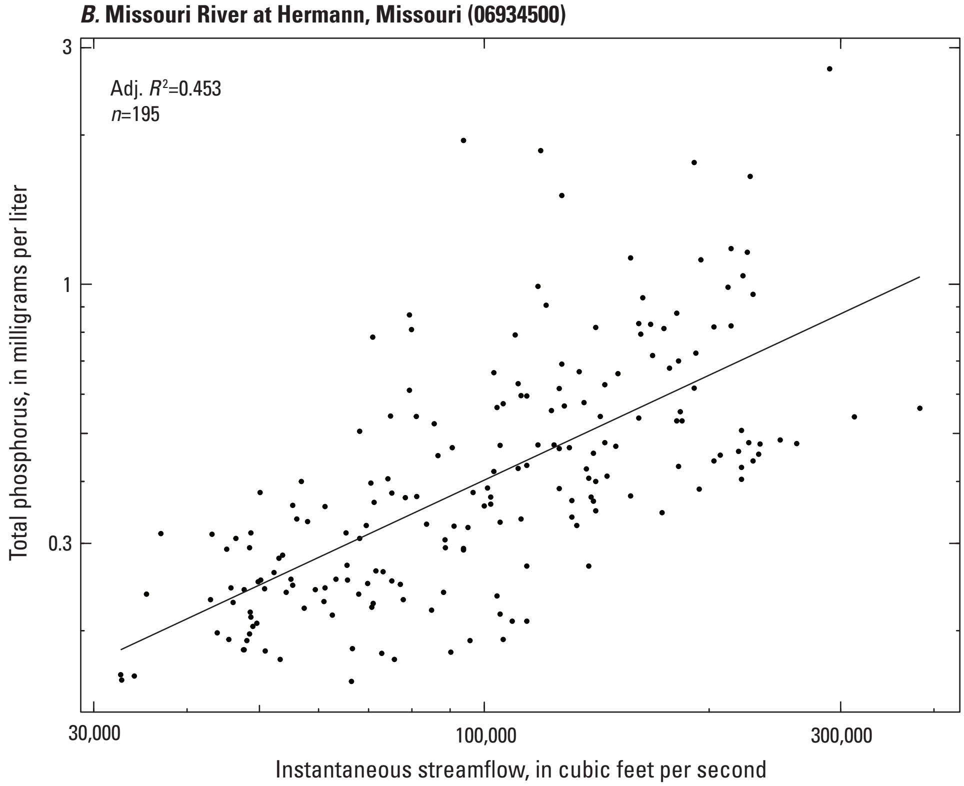
Data pair used in model

Best fit regression model

Model

log(*TP*)=0.74238×log(*Q*)−3.99724

***B.* Missouri River at Hermann, Missouri (06934500)**



EXPLANATION

[*TP*, total phosphorus concentration; Adj. R^2, adjusted coefficient of determination; *n*, number of values in dataset; *Q*, instantaneous streamflow]

Data pair used in model

Best fit regression model

Model

log(*TP*)=0.70306×log(*Q*)−3.91074

Figure 1.1. Total phosphorus streamflow-surrogate regression models at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

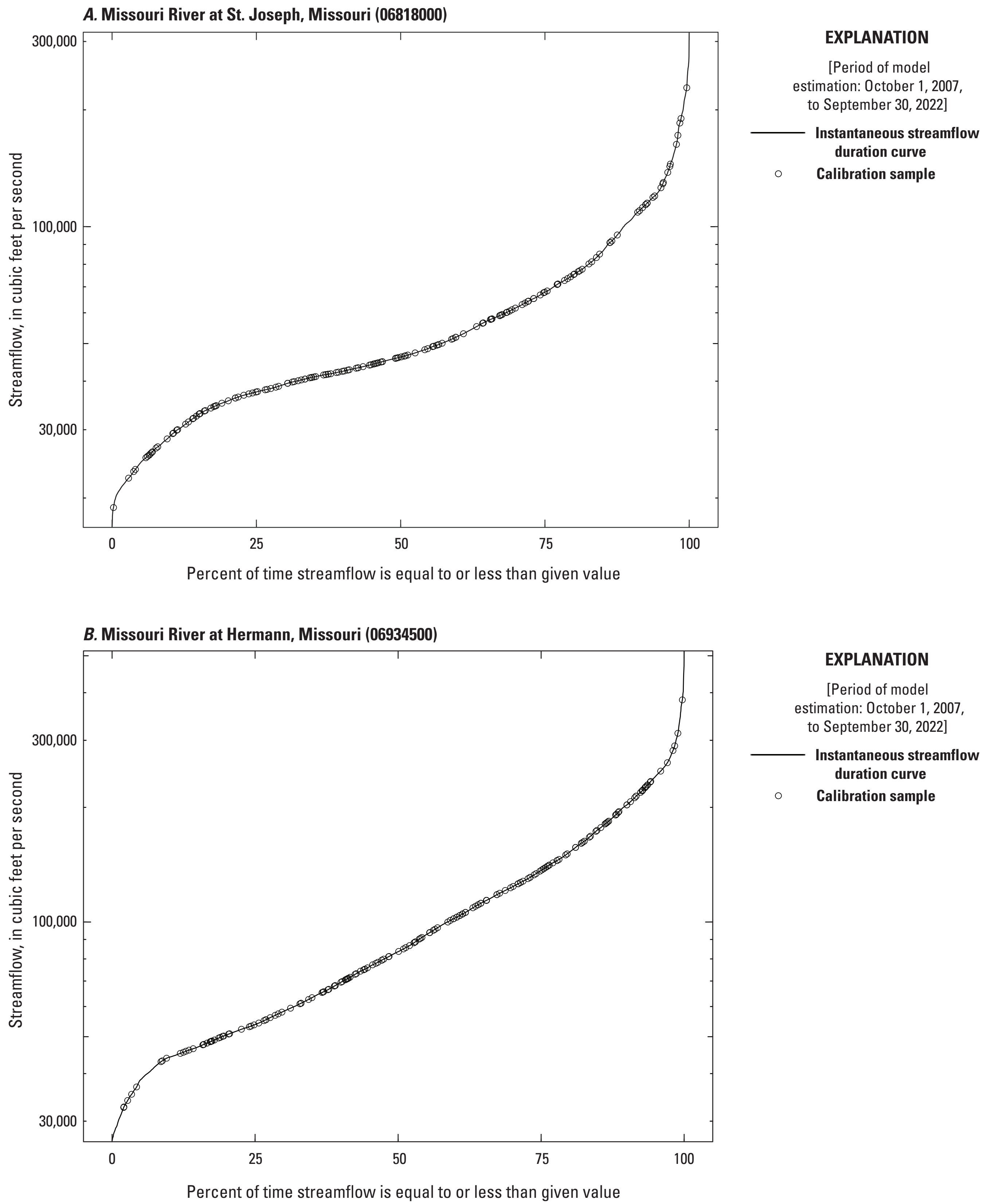


Figure 1.2. Graphs showing the streamflow duration curves with calibration samples at the Missouri River at St. Joseph, Missouri, streamgage (U.S. Geological Survey station 06818000) and the Missouri River at Hermann, Mo., streamgage (U.S. Geological Survey station 06934500).

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